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COMMERCIAL DEMONSTRATION OF THE NOXSO SO_2/NO_x REMOVAL FLUE GAS CLEANUP SYSTEM

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Project Definition Phase

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Prepared by

Morrison Knudsen Corporation
Ferguson Division
1500 West 3rd Street
Cleveland, Ohio 44113-1406

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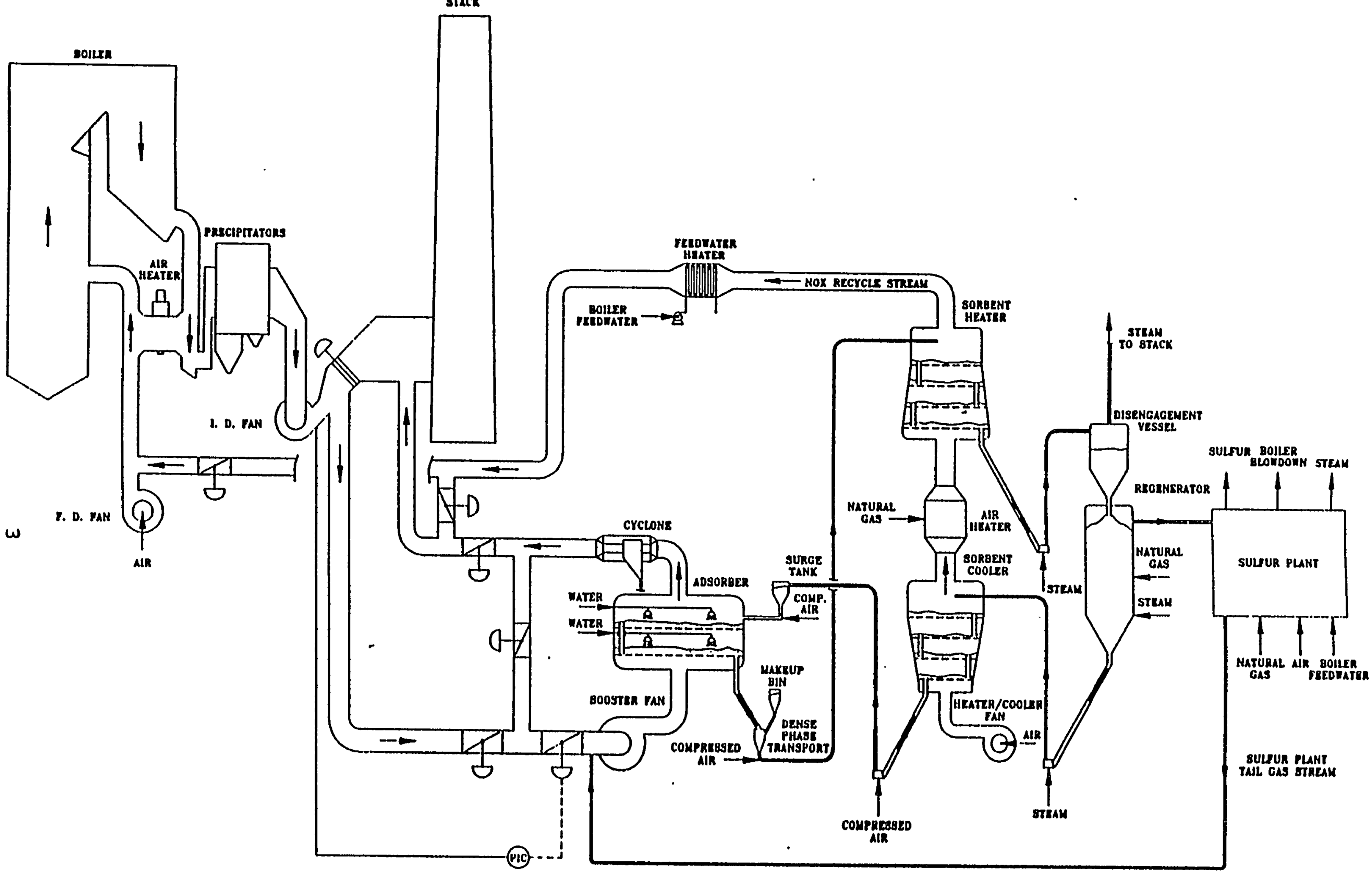


Figure 1-1. NOXSO Process Diagram

High temperature sorbent exiting the regenerator is conveyed to the multi-stage fluidized bed sorbent cooler. The sorbent flows counter to the ambient air which cools the sorbent. Regenerated sorbent exits the cooler at 295°F. It is then conveyed to the adsorber, completing the sorbent cycle.

Ambient air which is forced through the sorbent cooler by the heater-cooler fan exits the sorbent cooler at approximately 850°F. This preheated air then enters the air heater where it is heated to approximately 1325°F so it is capable of heating the sorbent exiting the sorbent heater to 1150°F.

2 PROJECT DESCRIPTION

The objective of the NOXSO Demonstration Project is to design, construct, and operate a commercial scale flue gas treatment system utilizing the NOXSO process. The effectiveness of the process will be demonstrated by achieving significant reductions in emissions of sulfur and nitrogen oxides. In addition, sufficient operating data will be obtained to confirm the process economics and provide a basis to guarantee performance on a commercial scale.

3 PROJECT STATUS

The project is currently in the project definition and preliminary design phase. This phase of the project was included to allow completion of the pilot plant testing before a significant design effort was expended. The NOXSO pilot plant test program was completed on July 30, 1993. Performance at the pilot plant exceeded the initial expectations for pollutant removal efficiency, sorbent attrition, and electrical power and natural gas consumption. Pollutant removal efficiency was enhanced significantly by the addition of the second bed in the adsorber and in bed water sprays to lower the adsorber temperature.

Data from the pilot plant has been incorporated into a fully integrated computer simulation which efficiently performs heat and material balances for the combined NOXSO plant, power plant, and sulfur plant system. The computer program also calculates sizes and capacities for the major process equipment. This computer simulation is used to evaluate process alternatives to determine their impact on process economics.

A preliminary process flow diagram and associated heat and material balances have been prepared for a commercial size plant. This flow diagram incorporates lessons learned from the pilot plant test program as well as results of laboratory process studies, theoretical process studies, and the computer simulation. Preliminary piping and instrumentation diagrams have been prepared for a commercial size plant based on the pilot plant experience and the preliminary process flow diagram.

Figure 3-1. General Arrangement with Structural Steel Supported Vessels

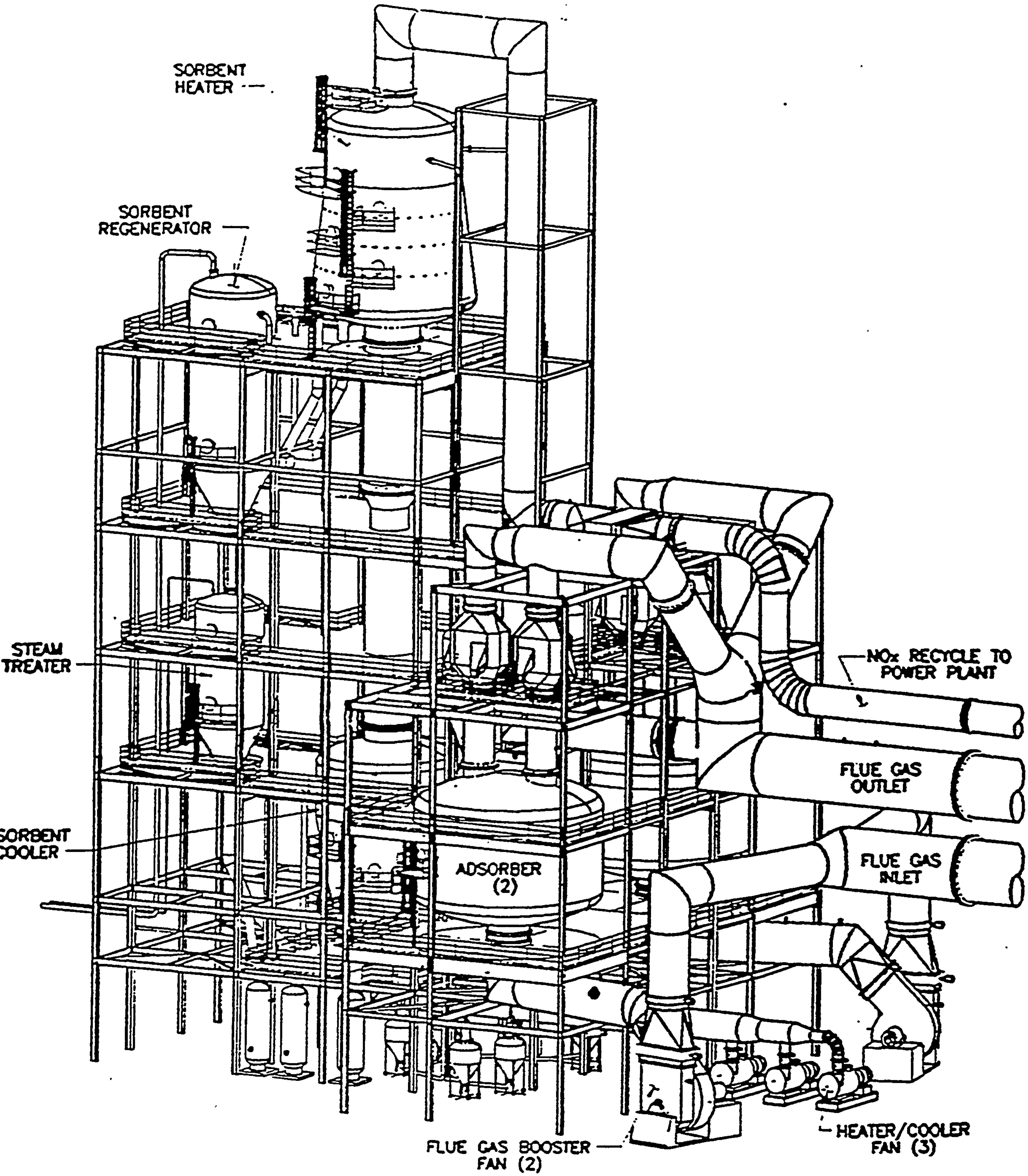
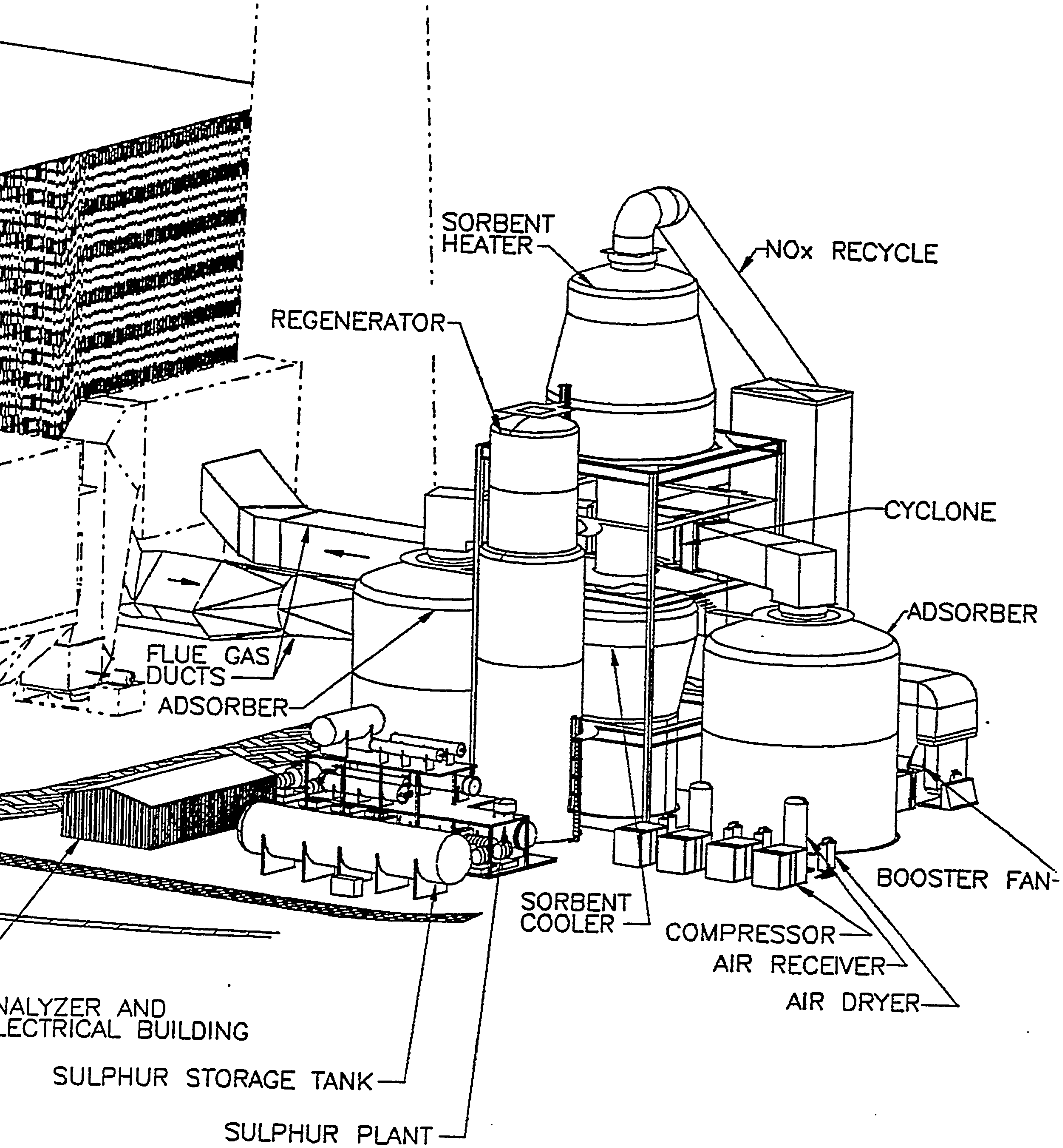


Figure 3-2. General Arrangement with Self Supporting Vessels



Positive internal design pressure of the adsorber, cooler and heater is based on the dead head pressure of the respective fans plus a margin to prevent lifting of the safety relief valves should the fans be dead headed. Negative internal (or external) design pressure is based on the maximum draft that the stack is capable of pulling, plus a margin to prevent opening the vacuum breakers.

Positive internal design pressure of the regenerator and steam disengagement vessel is set by the dead head pressure of the heater/cooler fan, the hydrostatic head exerted by the sorbent and a margin to prevent opening the safety relief device should this upset occur.

Design temperature of the adsorber is set by the power plant combustion air pre-heater discharge temperature at a reduced boiler load with full NO_x recycle flow. Added to this is the temperature rise across the booster fans and a safety margin bringing the typical value to 400°F. The allowable stress of carbon steels does not begin to decrease until 600°F is exceeded so the adsorber design temperature is not critical since it will never approach this value.

The design temperature of the sorbent heater and sorbent cooler is set by the sorbent regeneration temperature of 1150°F. To reach this sorbent temperature requires a sorbent heater gas inlet temperature to the sorbent heater of 1325°F. To provide a margin of safety, the sorbent heater design temperature is set at 1400°F. During normal operating conditions sorbent enters the sorbent cooler at 990°F. To provide a margin of safety, the sorbent cooler design temperature is set at 1050°F.

The regenerator and steam treater are refractory lined. The lining is both corrosion resistant and insulating, allowing the pressure boundary to be carbon steel. The lining is designed to provide a shell temperature of 130°F. The design temperature of the pressure boundaries of these vessels is 200°F.

The self supporting vessels require skirts to support them. The attachment point for the skirt is selected to minimize bending movements in the vessel wall and supporting skirt, resulting in a predominantly compressive load. The skirts are designed using the same code rules used for the vessels under the compressive load of their own weight. In contrasts, hanging vessels of this weight using mounting lugs exerts large bending moments on the vessel wall. To keep vessel wall stresses within allowable limits the walls must be thickened to accommodate the additional loading. To distribute the loads exerted by the lugs, circumferential rings are attached to the lugs and vessel wall. Consequently, the additional material required for the supporting skirt is substantially off-set by elimination of the mounting lugs, thickened vessel walls, and circumferential rings.

Specifically, to minimize high local stress concentration the skirt attachment point and head type are important. The ASME code suggests the use of 2:1 ellipsoidal heads with the mean diameter of the skirt coinciding with the mean diameter of the vessel. This is most important in the sorbent heater where local stress concentrations can lead to excessive creep and premature failure of the vessel.

The process vessel code calculations are in a spreadsheet format for flexibility in making changes. Appendix I of this report contains the adsorber calculations.

3.3.3 Plant Availability

To assure that lessons learned at the NOXSO pilot plant are incorporated in the commercial plant design, a detailed analysis of pilot plant availability was conducted. Additionally, using this study as a basis, availability of a commercial plant incorporating the lessons learned is estimated at greater than 99%.

The time period of pilot plant operation used for the analysis was April to December 1992. Most of the parametric testing took place during this time period and extra efforts were made to attain consistent, quality performance from the plant.

During this period, there were 37 instances in which the plant went off of flue gas. These shutoffs, or outages, ranged in time from 40 minutes to three weeks. Often just the flue gas needed to be shut off to take the necessary corrective action, other times the entire plant was shut down. After evaluation of the flue gas outages, each incident was categorized based on the cause of the occurrence. Figure 3-2 shows the reason for each outage, the cause of the event, and the number of times each event occurred during this time period.

3.3.3.1 Pilot Plant Gross Availability

The NOXSO pilot plant gross availability was 75%. The gross availability, as calculated in Figure 3-2 is the time spent processing flue gas divided by the time that flue gas was available for processing. The time that flue gas was available for processing is dependant on the power plant operations. The power plant unavailability was responsible for those events in Table 3-1 classified as "power plant". This time appears as host flue gas interruptions in Table 3-2.

The events and times listed under "less all outages" in Table 3-2 represent the remainder of the shutdowns listed in Table 3-1. For instance, "heater modification shutdowns" in Table 3-2 refers to "planned shutdowns" in Table 3-1. Also, "system checks and Mech./Elec. outages and repairs" refers to all of the mechanical and electrical failures listed in Table 3-1. They are listed in Table 3-2 this way to reflect the fact that while it was a mechanical or electrical failure which caused the outage, much of the corresponding downtime was spent making plant modifications, vessel inspections, instrument calibrations, etc. that were not related to the original cause of the outage. The distinction is made here because it will have a considerable effect on the pilot plant net and projected commercial plant availabilities.

Table 3-1. Pilot Plant Outage Events

Reason For Outage	Cause of Problem or Event	No.
Calibration drift*	MAC capacitance level probes needed recalibration	3
Mechanical failure	Sorbent heater grid warpage, grid hole pluggage & blown rupture disk	2
Mechanical failure	Regenerator control valve improperly seated	2
Mechanical failure	Hole in incinerator off-gas duct at steam inlet	2
Electrical failure*	MAC level probe failed due to disconnected wire	1
Mechanical failure	Top J-valve fluidizing grid plugged	1
Mechanical failure*	Flue gas fan bearings needed lubrication	1
Mechanical failure	Acid line clog caused adsorber grid pluggage	1
Electrical failure*	Power outage	1
Plant modification	DCS reconfiguration	1
Plant modification	Incinerator damper and control loop modifications	1
Planned shutdown	Sorbent heater grid warpage and grid hole pluggage	2
Operating conditions	Oversulfation of sorbent	4
Operating conditions	Adsorber grid pluggage caused by acid carryover	1
Operator error	Incinerator malfunction	1
Operator error*	Regenerator level gauge accidently shut off	1
Calibration	MAC calibration	2
Power plant	Power plant off line	7
Holiday	Thanksgiving & Christmas	2
Project review	Process shutdown	1

* Relevant failures for projected commercial availability calculations of Table 3-2.

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Operator error	Incinerator malfunction	1
Operator error*	Regenerator level gauge accidently shut off	1
Calibration	MAC calibration	2
Power plant	Power plant off line	7
Holiday	Thanksgiving & Christmas	2
Project review	Process shutdown	1

* Relevant failures for projected commercial availability calculations of Table 3-2.

Table 3-2. Pilot Plant Gross Availability

April-December 1992, total hours	6600
Less host flue gas interruptions	358
Host flue gas supply time	6242
Less all outages:	
NOXSO staff holidays	332
Project review days	138
DCS and incinerator modifications	48
Test envelope "events"	77
Test calibration shutdowns	21
Operator induced trips	14
Heater modification shutdowns	278
System checks and mechanical/electrical outages & repairs	653
Total hours	1561
Time on flue gas	4681
Gross Availability (4681/6242) x 100%	75%

3.3.3.2 Pilot Plant Net Availability

The pilot plant net availability is calculated considering the pilot plant as a commercial venture, in other words, as if the operations attempted to maximize availability. The result of this view is that the calculated time the plant is not available includes time in which the plant was mechanically unable to process flue gas, due to either equipment failures or trips, but excludes: those failures related to equipment needed solely for pilot plant operations (e.g. regenerator off-gas incinerator, which would not be present in a commercial system), tests which measured the limits of the process performance envelope, outage periods for equipment modifications or calibrations, project staff review meeting days, and staff holidays. The downtimes falling under these categories are considered as time that would have been spent on flue gas in a commercial environment. Consequently, the pilot plant net availability was calculated at 97%, as shown in Table 3-3.

Table 3-3. Pilot Plant Net Availability

Host flue gas supply time, hours	6242
Less outages not due solely to tests*:	
Operator induced trips	5
Heater shutdowns	87
Mechanical/electrical outages repairs and repairs	96
Total hours	188
Adjusted POC time on flue gas	6054
POC Net Availability (6054/6242) x 100%	97%

*Excludes failures of equipment unique to the pilot plant, equipment failures in pushing the performance envelope, planned outages for plant modifications, and other outages listed:

NOXSO staff holidays	332
Project review days	138
DCS and incinerator modifications	48
Test envelope "events"	77
Test calibration shutdowns	21
Operator induced trips	9
Heater modification shutdowns	191
System checks due to mechanical/electrical outages	557
Total hours	1373

The mechanical and electrical failures, and the system trips were analyzed on a case by case basis to determine the effect of each event on the net availability. In each case, the total down time was divided into actual repair time and the follow up time for system checks and other modifications. The downtime in each case was then adjusted so that only the time used for repairs is counted against the net availability. The remainder of the time is considered as time which would have been spent on flue gas under normal, commercial operating circumstances.

3.3.3.3 Failure Analysis

Several pilot plant problems have been solved through design iterations which eliminate the potential of these problems recurring at commercial installations. The design solutions to the outages listed in Table 3-1 are presented here, and summarized in Table 3-4.

Table 3-4. Design Changes Based on Pilot Plant Performance

Problem	Solution
Warpage of sorbent heater grids	Grids redesigned for differential thermal expansion
Pluggage of sorbent heater grid holes	Sorbent heater designed for correct TDH between grids
Pluggage of J-valve fluidizing grid	J-valves replaced with L-valves
Unseated regenerator pressure control valve	Off-gas lines designed with redundant valve in parallel
Blown rupture disk in sorbent heater disengaging vessel	No sorbent heater disengaging vessel in commercial design
Calibration drift in dense phase transport capacitance level probes	Switch to vibrating wand probe
Frequent lubrication of 3600 rpm direct drive fan bearings	Low speed utility service fans will eliminate problem
Adsorber grid pluggage by acid line clog	In-bed cooling eliminates the need for the acid line
Various incinerator failures	No incinerator needed for commercial service. Incinerator needed for the sulfur recovery unit is specifically designed for that purpose

The sorbent heater at the pilot plant created several outages, but they were mechanical in nature and not process flaws. First, there was the thermal expansion which caused the grids to warp and restrict movement of the flapper valves of the downcomers. This was due to the grid sections being welded together and spot welded to supports which anchored them to the vessel walls not allowing for thermal expansion. The redesign of the grids, and their construction, for commercial plants includes rolled edges and vertical clamping of the grid sections. This will allow the grid holes to be continued across the joints without loss of fluidization area. By clamping the grid outer edges between rolled angles with bolts and bolting the center support angles to support shoes, the design allows for differential thermal expansion without buckling of the material. This construction technique has been successfully tested at the pilot plant when the second grid was added to the adsorber vessel. The other problem which plagued the sorbent heater, grid hole pluggage, was a result of insufficient transport disengaging height (TDH) between the fluidized bed and the grid above it. This problem is solved by providing adequate TDH.

The J-valves are dilute phase transport devices which serve a dual purpose of transporting the sorbent from vessel to vessel while forming a seal to prevent the mixing of gases between vessels. The primary problem with the design is the use of internal distributor plates which plugged over time resulting in a degradation of valve performance. The solution to this problem was the design, testing, and integration of an L-valve. The L-valve, which was also successfully tested at the pilot plant, has no internal grids; it also proved to be simpler in design, more reliable in performance, easier to control, and its gas requirements are essentially the same as the J-valves.

When the rupture disk failed in the sorbent heater disengaging vessel it was because of sorbent heater and J-valve problems. If sorbent could not move through the heater and into the regenerator, it backed up into the disengaging vessel causing elevated pressures which ruptured the disk. The disengaging vessel was supplied as part of the dense phase transport system and through the operation of the pilot plant was found to have no practical value to the NOXSO Process. Commercial designs will not include a sorbent heater disengaging vessel.

The pressure control valve in the regenerator off-gas lines also caused flue gas outages. These outages were due to the valve being improperly seated. While this type of problem may occur at a commercial installation, the off-gas lines in the commercial unit are designed with a redundant valve in parallel which would automatically be placed into service in the event of a failure in the primary valve.

The capacitance level probes used in the dense phase transport system had a quick recalibration procedure requiring only that the operator empty the fluidizing vessel and then hold a button in for about 20 seconds in the sensing module electronics enclosure. The problem with these probes was that they would frequently experience calibration drift to the point of failure. Vibrating wand type level probes were also used at the pilot plant in other services with little or no trouble at all, thus it will be this type of probe which will be used in the dense phase transport service of commercial plants.

Both of the fans used at the pilot plant operated at 3600 rpm and experienced failures due to the high speeds and lack of vibration monitoring equipment. By using low speed, utility service fans these problems will be avoided at commercial installations.

The problem which caused the adsorber grid pluggage has been eliminated by in-bed cooling. With duct cooling, there was acid formation upstream of the adsorber which had to be removed by an acid line. When a clog developed in an elbow of that line, acid backed up into the duct and was carried into the adsorber, plugging the grid. In-bed cooling precludes the formation of acid upstream of the adsorber since the temperature of the flue gas is maintained above the acid dewpoint in the ductwork.

The incinerator was a bottom fired vessel which burned the regenerator off-gas to convert all sulfur species to SO_2 to return to the power plant stack. However, the incinerator had several problems at the pilot plant (it was not specifically designed for this service), this incinerator is not required in a commercial plant in which the regenerator off-gas is fed to a sulfur recovery unit.

3.3.3.4 Projected Commercial Plant Availability

The projected availability of a commercial system was calculated assuming commercial operating conditions and incorporation of the design improvements from the pilot plant test program. Because a commercial unit will not be intentionally stressed to evaluate component performance as was done at the pilot plant, it is anticipated that commercial service will be much less severe. Also, institution of the proposed design improvements will preclude repeating many of the problems which were experienced at the pilot plant. Those events in Table 3-1 marked with an asterisk are relevant to this calculation. Results of this calculation project commercial availability to be greater than 99%, as shown in Table 3-5.

Table 3-5. Projected NOXSO Commercial Plant Availability

Equivalent host flue gas supply time, hours	6242
Projected commercial outages*:	
Operator induced trips	5
Mechanical/electrical outages and repairs	11
Total hours	16
Projected time on flue gas	6226
Predicted NOXSO Commercial Availability (6226/6242) x 100% >99%	

3.3.4 Equipment Sparing

As estimated in the previous section, the availability of the commercial NOXSO plant will be greater than 99%. To accomplish this high level of availability, installed spares will be provided as indicated in Table 3-6. Spared equipment is categorized as rotating equipment, control valves, and solids transport systems. A brief discussion of the equipment sparing by category follows.

Table 3-6. Equipment Sparing

Rotating Equipment	
Booster Fans	2 x 60%
Heater/Cooler Fans	3 x 50%
Air Compressors	
Low Pressure	2 x 50%
High Pressure	2 x 100% (spare for L.P. and H.P)
Boiler Feedwater Pump	2 x 100%
Control Valves	
Severe Service	Automatic valve in parallel
Normal Service	Manual valve in parallel
Solids Transport	
Dense Phase	2 x 60%
L-Valves	2 x 60%
Sulfur Plant	
Booster Fan	2 x 100%
Combustion Fan	2 x 100%
Oil Pump	2 x 100%
Sulfur Pump	2 x 100%

3.3.4.1 Rotating Equipment

In general, all rotating equipment will be spared. The sorbent heater/cooler air will be provided by two of three 50% capacity fans. The boiler feedwater to the NO_x recycle cooler will be provided by one of two 100% capacity pumps. A second 100% capacity 100 psig air compressor (for instrument air) will provide a spare for the 100 psig air compressor as well as for either of the two 50% capacity 50 psig air compressors used for the dense phase transport system and air driven L-valves. The two adsorbers will each be served by one 60% capacity fan. If one flue gas booster fan fails, the remaining flue gas train will be isolated and the NOXSO plant capacity will be reduced to the 60% capacity of a single train.

In the sulfur plant, the rotating equipment is also spared. The booster fan and combustion air blower are each provided with a 100% capacity spare. Also, the oil circulation pump and the main sulfur tank pump are each provided with a 100% capacity spare.

3.3.4.2 Control Valves

All control valves will be equipped with isolation valves and at least a manual throttle valve in parallel with the primary valve. In the event of a failure, the plant could continue to operate by manually regulating the spare valve while the automatic valve is repaired. Those valves which could not be manually regulated, in the event of a failure in the primary valve, will be provided with an automatic valve in parallel.

3.3.4.3 Sorbent Transport Systems

The dense phase transport system which transports sorbent from the adsorbers to the sorbent heater is comprised of two fluidizers and control valves for each adsorber. In the event that one of these fails, sorbent circulation can be maintained at a slightly reduced rate; however, the sorbent circulation rate would be higher to one adsorber than the other. The dilute phase transport systems which transport sorbent from the sorbent heater to the regenerator, from the regenerator to the sorbent cooler, and from the sorbent cooler to the surge tank, will each be equipped with two 60% capacity L-valves.

3.4 Nitrogen Oxide Studies

No nitrogen oxide studies were conducted during this reporting period.

3.5 Process Studies

3.5.1 Sorbent Heater/Cooler Energy Balance

Recent process studies of the sorbent heater and sorbent cooler energy balances have attempted to quantify water adsorption on the NOXSO sorbent, while examining the effect of water adsorption/desorption on the design of the sorbent heater/cooler train of the demonstration plant.

Previously, it was proposed that water adsorption and desorption in the sorbent cooler and sorbent heater, respectively, were the cause for the deficient energy balance closures experienced at the pilot plant. This proposal has been verified through an examination of heat utilization efficiencies and by an uncertainty analysis (presented in Quarterly Technical Report No. 11). In order to fully quantify this effect, it is necessary to experimentally generate a set of water adsorption isotherms specific to the NOXSO sorbent. This would require an extensive laboratory effort. In order to obtain more immediate data, laboratory adsorption tests simulating water adsorption in the adsorber using NOXSO low density sorbent will be conducted. This will provide adsorption data points which may be used to reconcile the sorbent heater energy balance by quantifying the water content of sorbent entering the sorbent heater. These laboratory tests are in progress.

A study has been conducted which examines the effect of water adsorption on the design of the sorbent heater/cooler train. This analysis uses the most recent computer simulation of the NOXSO process to obtain demonstration plant stream data with no water adsorption/desorption taking place. By individually treating the sorbent heater and sorbent cooler, water desorption and adsorption are included in a heat transfer analysis to determine the effect on the required gas mass flows and vessel off-gas temperatures. The methods, assumptions, and results of this study are presented next.

This study relies on the computer simulation to provide the data which forms the starting point for the water adsorption/desorption analysis. The simulation provides information for the sorbent heater and sorbent cooler, including: the number of vessel stages, the sorbent mass flow rates, the sorbent inlet temperatures, the sorbent outlet temperatures and the gas inlet temperatures. As water adsorption/desorption is included in the analyses, the object is to find the gas mass flows and off-gas temperatures at which the systems reach thermodynamic equilibrium for each value of water content of sorbent entering the heater or exiting the cooler.

Assumptions made for the analyses are as follows. Each fluid bed is treated as two continuous stirred tank reactors (CSTR) in series. The gas does not mix between the stages. In the case of the sorbent heater, all of the water is considered to be desorbed in the top stage; In the case of the sorbent cooler, all of the water is considered to be adsorbed in the bottom stage. Also, the water heat of adsorption is considered to be a constant equal to 1250 Btu/lb. Finally, in these analyses, ambient heat losses are not included; ambient losses have been shown to be about one percent of the heat input of the system, and for these analyses this is considered inconsequential.

By performing an energy balance around each fluidized bed in the vessels, the following equations are developed. In the analysis of the sorbent heater, the following two equations are used.

For the top bed, in which water desorption is taking place,

$$m_s * c_{p_s} * (T_{s_o} - T_{s_i}) + m_s * X_{H2O} * h_{A_{H2O}} = m_g * c_{p_g} * (T_{g_i} - T_{g_o})$$

In the remaining three beds,

$$m_s * c_{p_s} * (T_{s_o} - T_{s_i}) = m_g * c_{p_g} * (T_{g_i} - T_{g_o})$$

In the analysis of the sorbent cooler the following two equations are used:

For the bottom bed, in which water adsorption is taking place,

$$m_s*c_{p_s}*(T_{s_i}-T_{s_o})+m_s*X_{H2O}*h_{A_{H2O}}=m_g*c_{p_g}*(T_{g_o}-T_{g_i})$$

In the remaining three beds,

$$m_s*c_{p_s}*(T_{s_i}-T_{s_o})= m_g*c_{p_g}*(T_{g_o}-T_{g_i})$$

In the above equations a subscript s indicates a sorbent variable and a subscript g indicates a gas variable, additionally:

m	= mass flow, lb/hr
c_p	= specific heat, Btu/lb/°F
T_i	= inlet temperature, °F
T_o	= outlet temperature, °F
X_{H2O}	= sorbent water loading, $lb_{H2O}/lb_{sorbent}$
h_{AH2O}	= water heat of adsorption, Btu/lb_{H2O}

Also, in each case the specific heats are calculated using the following two equations:

$$c_{p_s}=[22.08+0.008971*T-522500/T^2]/102$$

$$c_{p_g}=[6.8717+0.000844*T-39417/T^2]/28.84$$

where T is the logarithmic mean temperature in degrees Kelvin and c_p is in Btu/lb/°F.

The water content of sorbent entering the sorbent heater is determined by the adsorber temperature, flue gas water content, adsorber in-bed water sprays, and the sorbent water loading characteristics. The analysis was conducted for sorbent entering the sorbent heater with water contents ranging from 0 to 7 percent. This range spans the expected sorbent water content based on typical adsorber operating conditions and water adsorption characteristics for commercially available activated alumina. Sorbent exits the sorbent heater at 1150°F containing a negligible amount of water.

Sorbent enters the sorbent cooler at approximately 1000°F containing a negligible amount of water. In the sorbent cooler, ambient air is used to cool the sorbent, consequently the water content of the cooling air is determined by the ambient air temperature and humidity. For the cooler analysis, the amount of water adsorbed by the sorbent is varied from 0 to 3 percent which spans the expected range based on the range of ambient conditions, sorbent mass flow rate, cooling air flow rate, and water adsorption characteristics for commercially available activated alumina.

Figure 3-3 and Figure 3-4 show the results of these analyses for the sorbent heater and cooler, respectively. As seen in the figures, the overall effect on heating and cooling the sorbent

Figure 3-3. Energy Balance Water Effect - Sorbent Heater

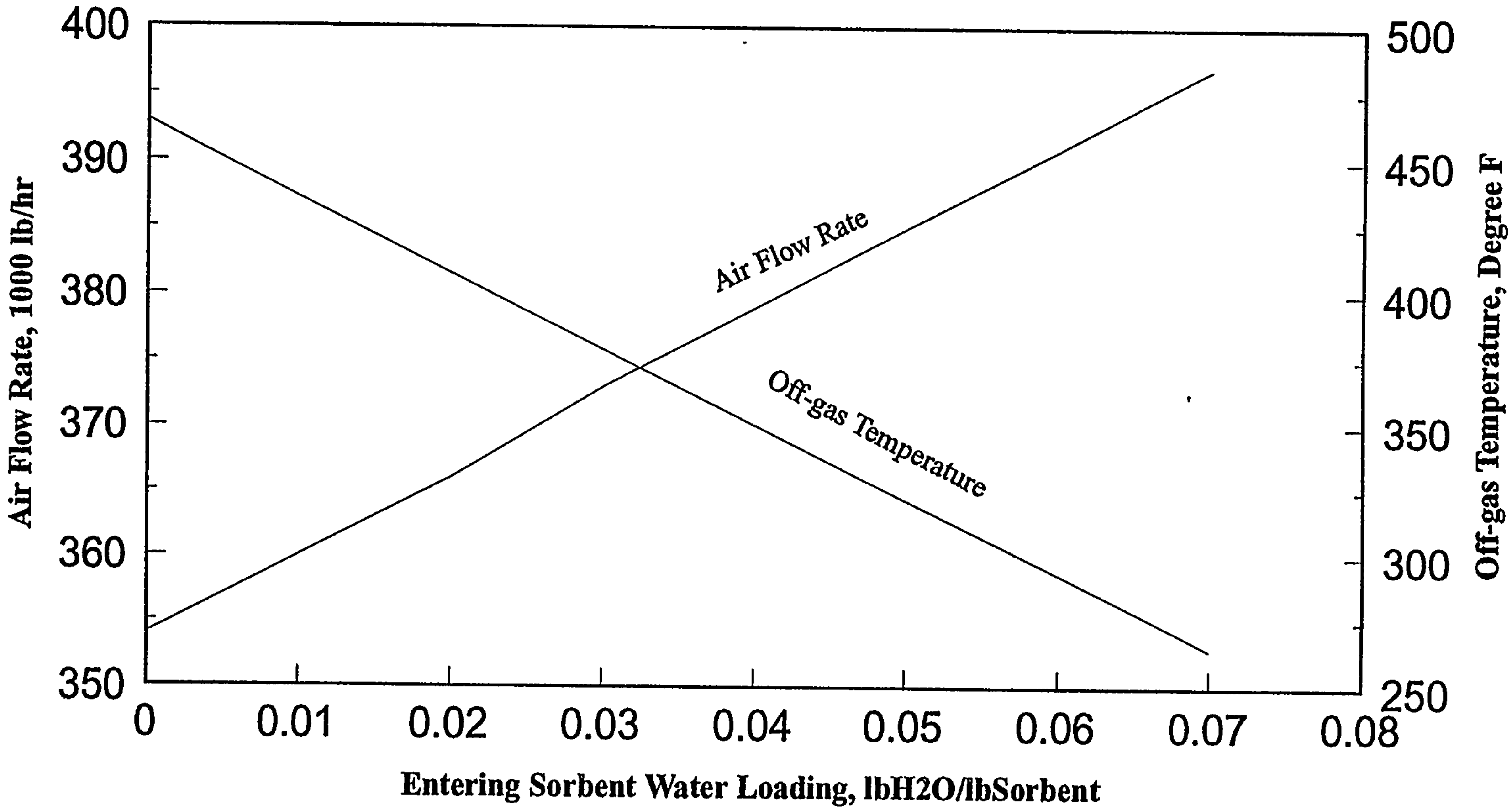

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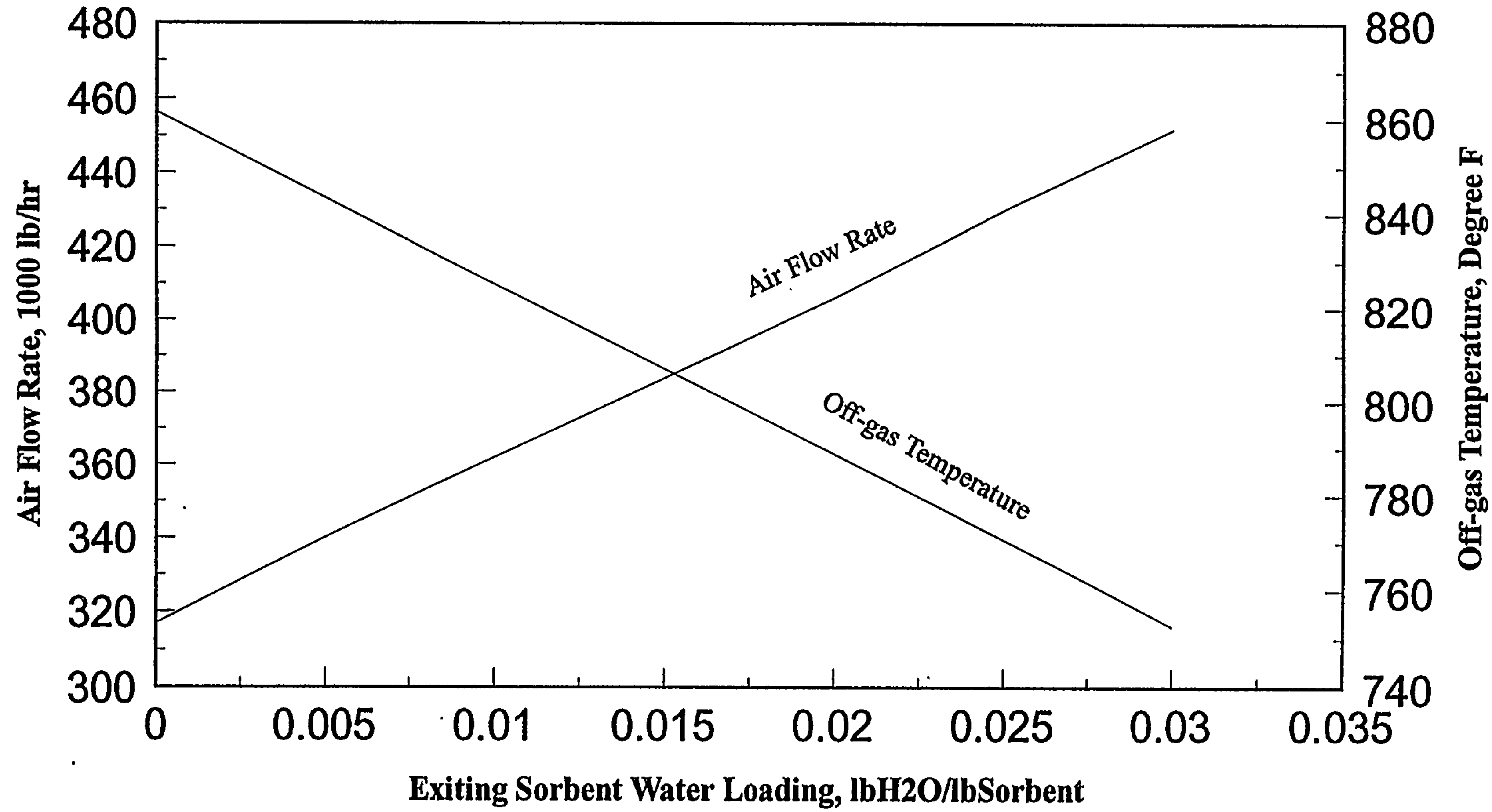
Figure 3-4. Energy Balance Water Effect - Sorbent Cooler



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is similar in both cases. In the sorbent heater and sorbent cooler, as the amount of water desorbed or adsorbed respectively is increased there is an increase in the amount of gas required to heat or cool the sorbent as well as a decrease in the temperature of the off-gas stream. The effects of water adsorption and desorption on plant design include increased heater/cooler fan size and power consumption, increased natural gas consumption in the air heater, but also an increase in the energy credit generated by the sorbent heater off-gas stream. However, the overall impact on the capital and operating costs of the NOXSO process is small because the energy required to adsorb and desorb water is small compared to the total energy transferred in the sorbent heater and sorbent cooler.

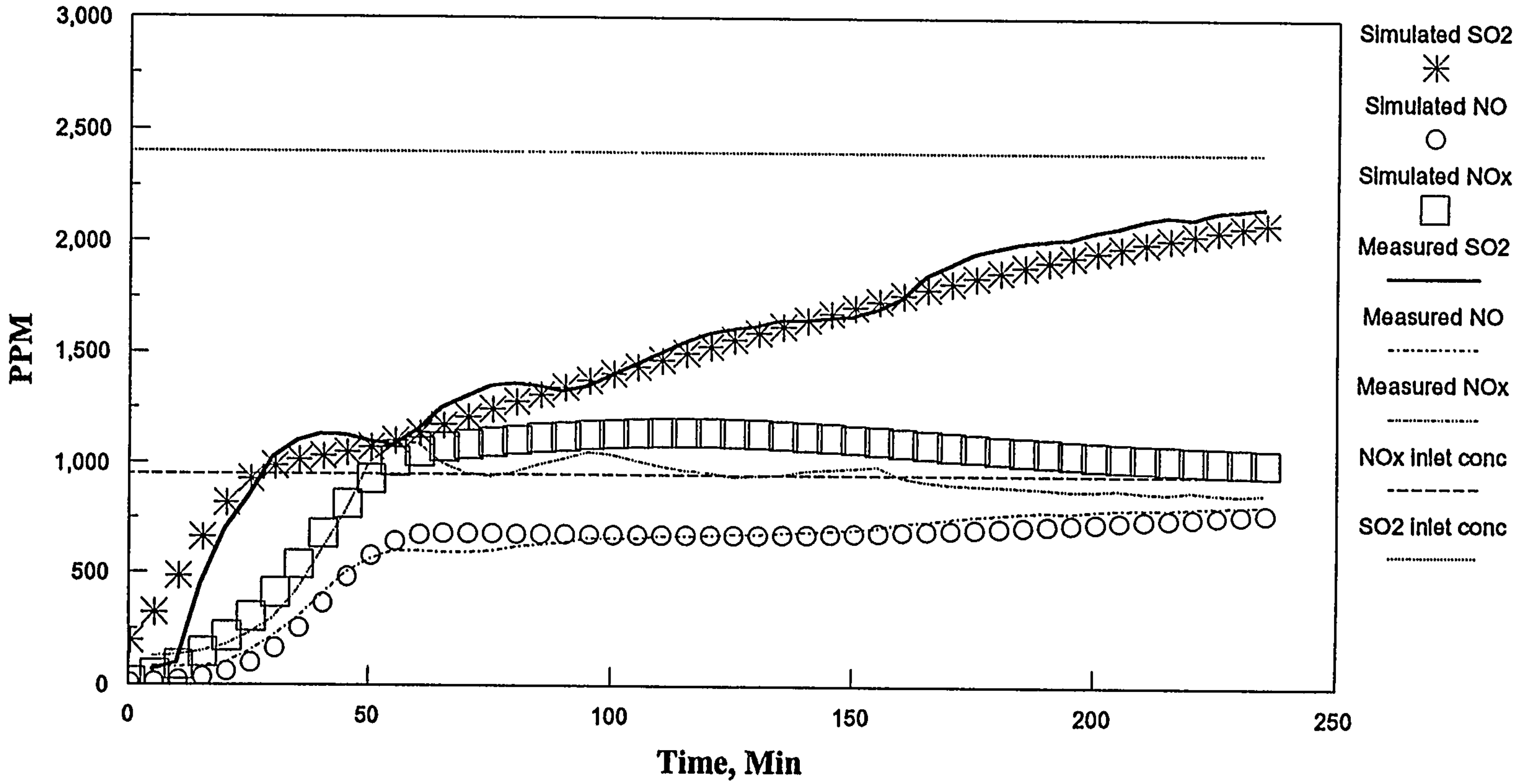
3.5.2 Adsorber Model

Simulation of the Laboratory Fixed-Bed Sorption Data

In the last quarterly report, we summarized the work to simulate the 120°C fixed-bed sorption tests. Using the least-squares method, we determined the sorbent capacities for the SO_2 and NO_x sorption and the reaction rate constants at 120°C. Similar work was conducted to simulate a 180°C fixed-bed sorption test. This time all eleven parameters, four sorption sites and seven rate constants, were determined from a single test. Since the resultant 180°C constants show some discrepancy with those from 120°C, we repeated the least-squares fit with the 120°C data. The match between measured and simulated exit concentrations is excellent for both temperatures with the exception of the NO_x concentration for the 120°C test as shown on Figure 3-5 and Figure 3-6. Even for NO_x at 120°C, the measured NO_x is at worst 20% below the simulated value. This can possibly be attributed to temperature fluctuations in the experiments. At this time, we decided not to wait for the laboratory to repeat the tests, but to extend the modelling work to simulate the POC fluid-bed sorption data. Hopefully, the large scale data will help pinpoint the errors. The semi-final sorbent capacities and sorption rate constants obtained from the 120°C and 180°C fixed-bed data and used to generate the simulated results on Figure 3-5 and Figure 3-6 are tabulated in Figure 3-6. Clearly, the temperature has an important effect on the sorption. Both NO_x and SO_2 break through earlier at 180°C than for the case of 120°C.

In general, the simulation results show that the sorption sites decrease with increasing temperature, while the sorption rate does the opposite. But two exceptions are found in Table 3-7. One, the alumina SO_2 sorption sites, Al(1) increase with temperature. Two, the rate constant of $2NaNO_3 + SO_2 \dashrightarrow Na_2SO_4 + 2NO_2$ reaction, k9, decreases with increasing temperature. We suspect the abnormal trend was caused by trying to determine too many parameters with too little laboratory data.

Figure 3-5. Fixed Bed Adsorption @ 120C

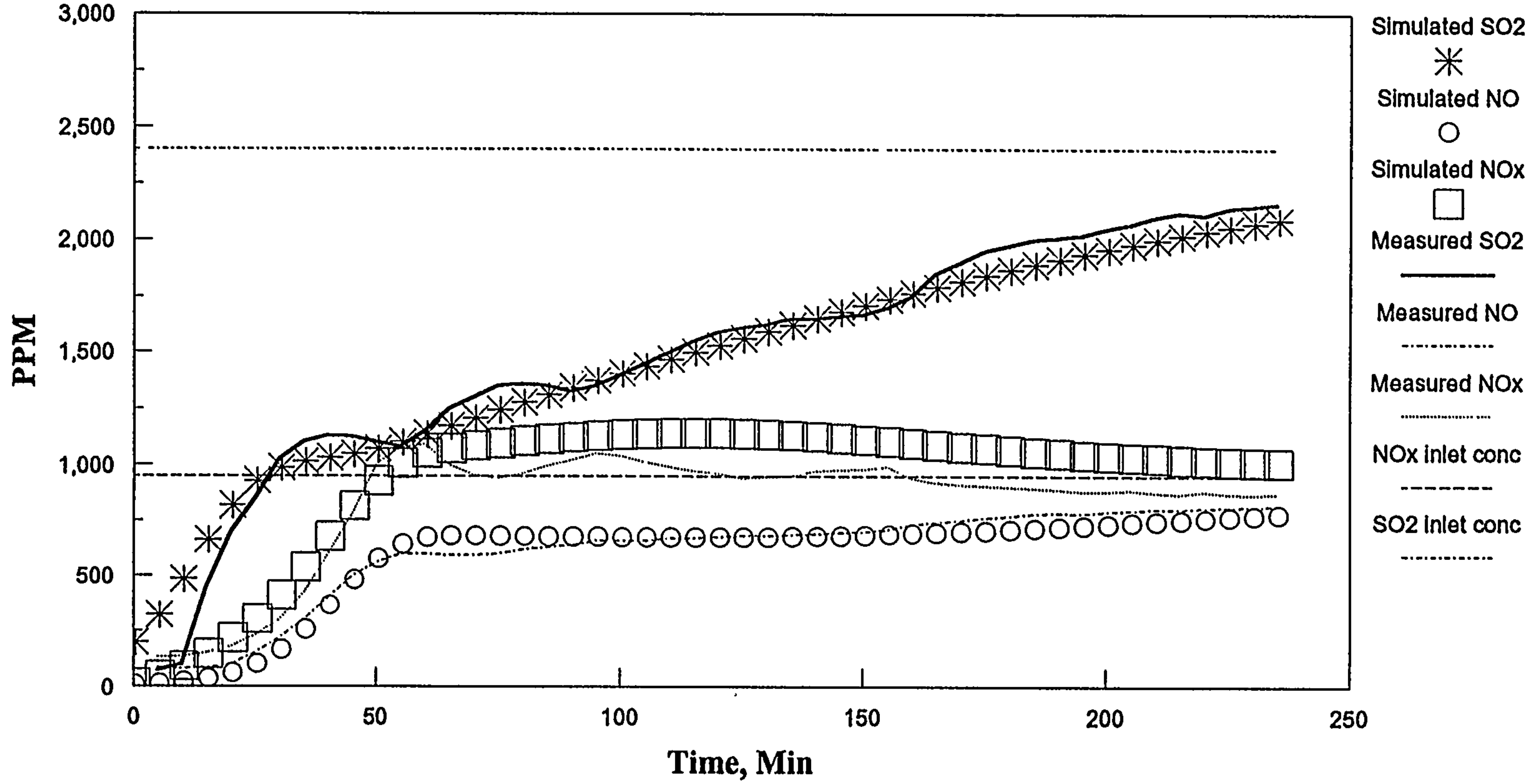


Sorbent - 30 g POC-40

Gas - 5 slpm with 2400 ppm SO2, 950 ppm NOx, 2%

a:q12_3_5.pre

Figure 3-6. Fixed Bed Adsorption @180C



Sorbent - 30g POC-40

Gas - 5 slpm with 2450 ppm SO2, 965 ppm NOx, 2%

a:q12_3_6.pre

Table 3-7. Sorbent Capacities and Rate Constants for Sorption

	180°C	120°C
Al(1)	0.9222	0.752
Al(2)	0.3505	0.76
Na_2O(1)	3.7054	5
Na_2O(2)	0.0443	1.18
k1	1074.5237	681.2
k2	2881.9726	2210.85
k4	272.7469	132.6306
k5	14.2523	2.6455
k6	5.0472E8	5.0472E8
k8	7887.918	317.26
k9	7.3539	49.8196

Simulation of the POC Fluid-bed Sorption Data

The POC adsorption data were obtained from a 10.5 ft diameter fluidized-bed reactor. The POC tests were conducted with various operating conditions. The variables changed during the operation period were adsorber temperatures, sorbent inventories, gas and sorbent flow rates, NO_x and SO_2 inlet concentrations, with and without in-bed water spray, and single and two stage fluid-bed arrangements. This wide spectrum of test data serves as the best tool to verify the adsorber model. Before applying the parameter values obtained from the fixed-bed data to simulate the POC fluid-bed results, we have to approximate the temperature effect on the sorption. To keep the model simple, we assume the change of sorption sites is linearly proportional to the temperature change, and the changes of sorption rates obey Arrhenius' law.

The major difference between the fixed-bed and the fluid-bed is the gas-solid contact pattern. Theoretically, if there is a model to properly describe the gas-solid contact pattern in the fluid-bed, then there is a straight forward application to use the fixed-bed rate constants to simulate a fluid-bed reactor. Many such models are available in the literature, among them the bubbling-bed type models are the best. For the NOXSO fluid-bed adsorber, we selected the Bubble-Assemblage Model (BAM) to describe the gas-solid contact pattern. The BAM model was invented by C.Y. Wen and L.T. Fan[1], and generalized by M.H. Peters, L.S. Fan and T.L. Sweeney[2].

Figure 3-7. Comparison of SO2 Removal Efficiency for POC Fluid Bed Adsorber

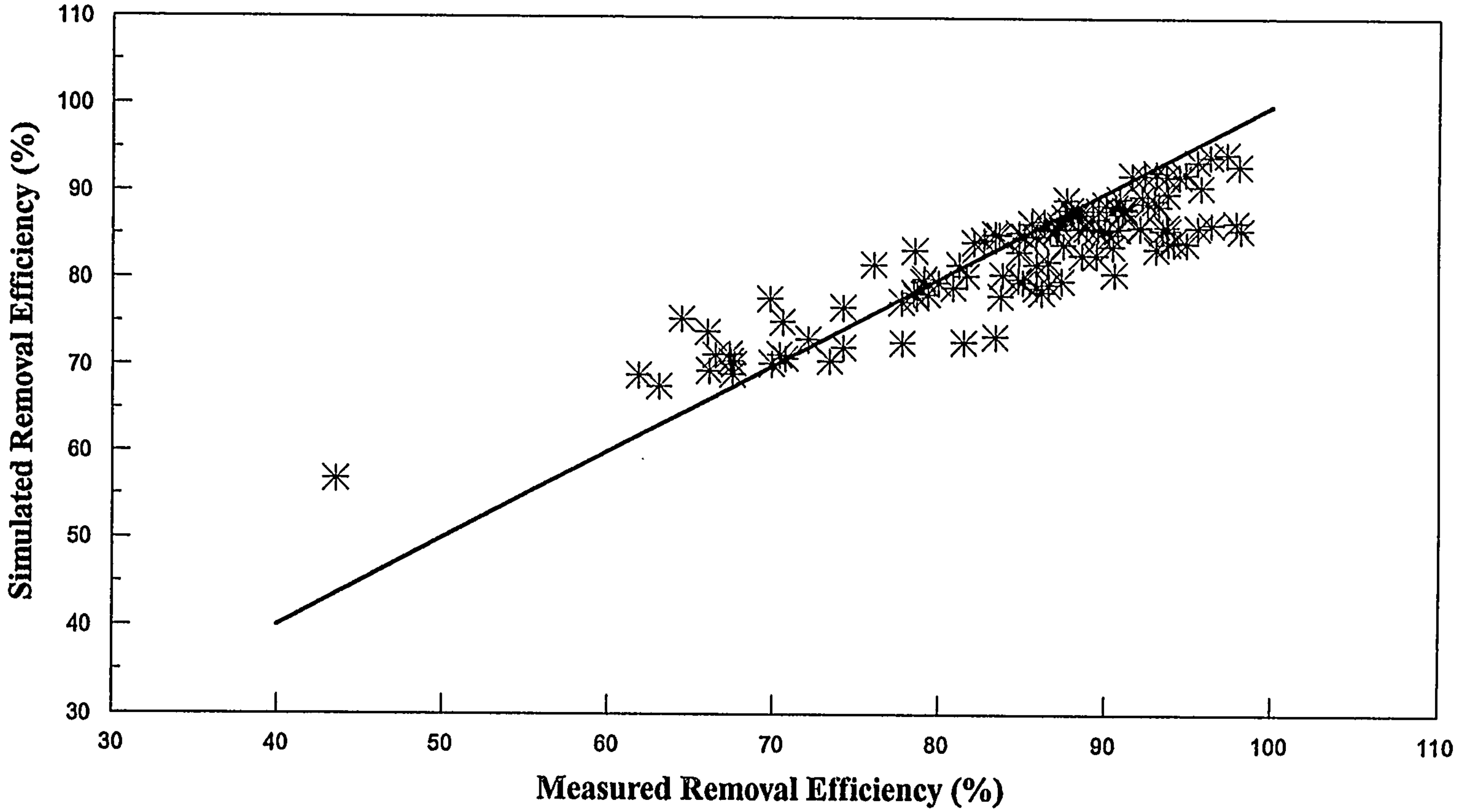


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Figure 3-8. Comparison of NOx Removal Efficiencies for POC Fluid Bed Adsorber

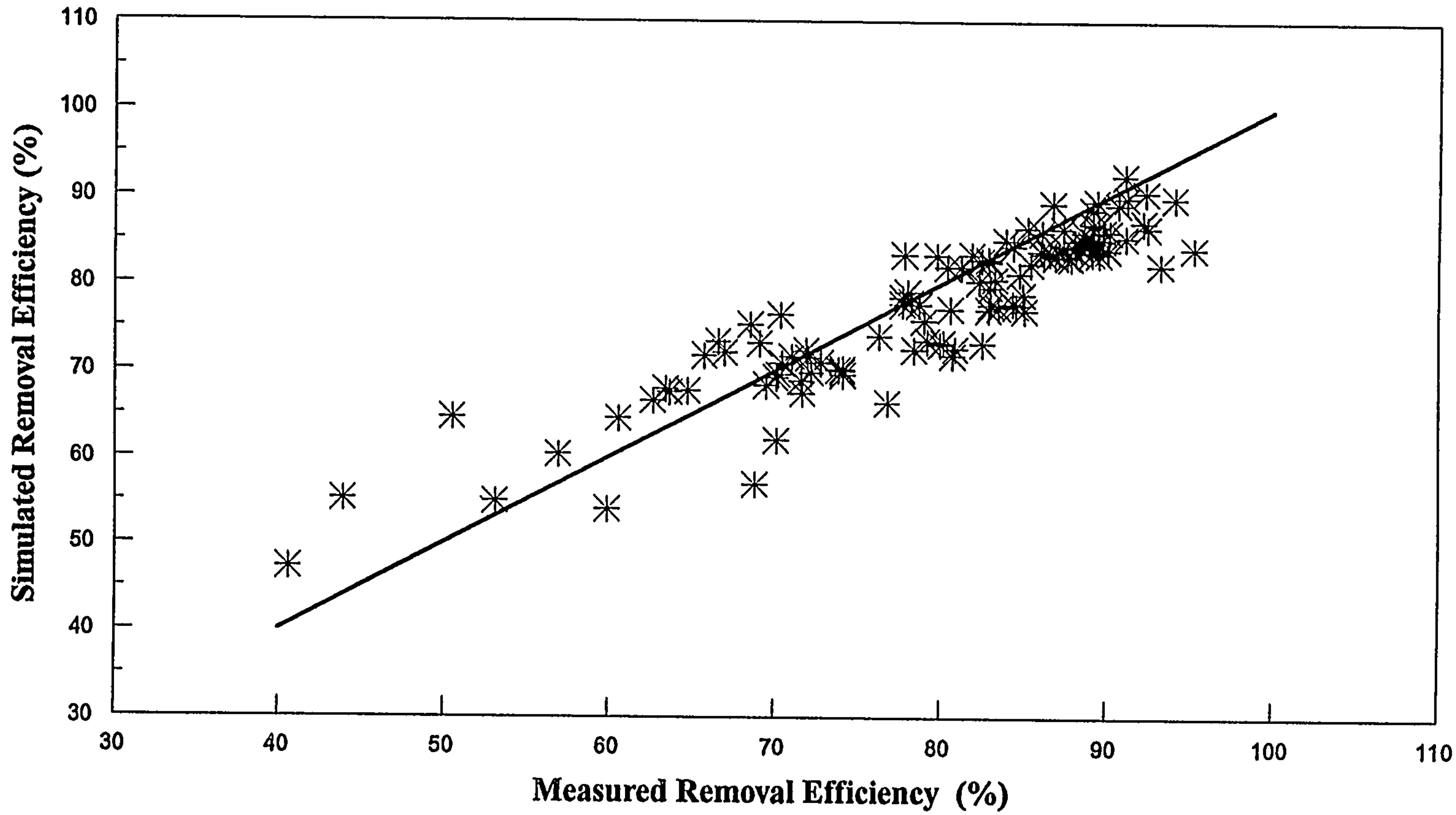

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Figure 3-9. Inlet NOx Concentration Effect

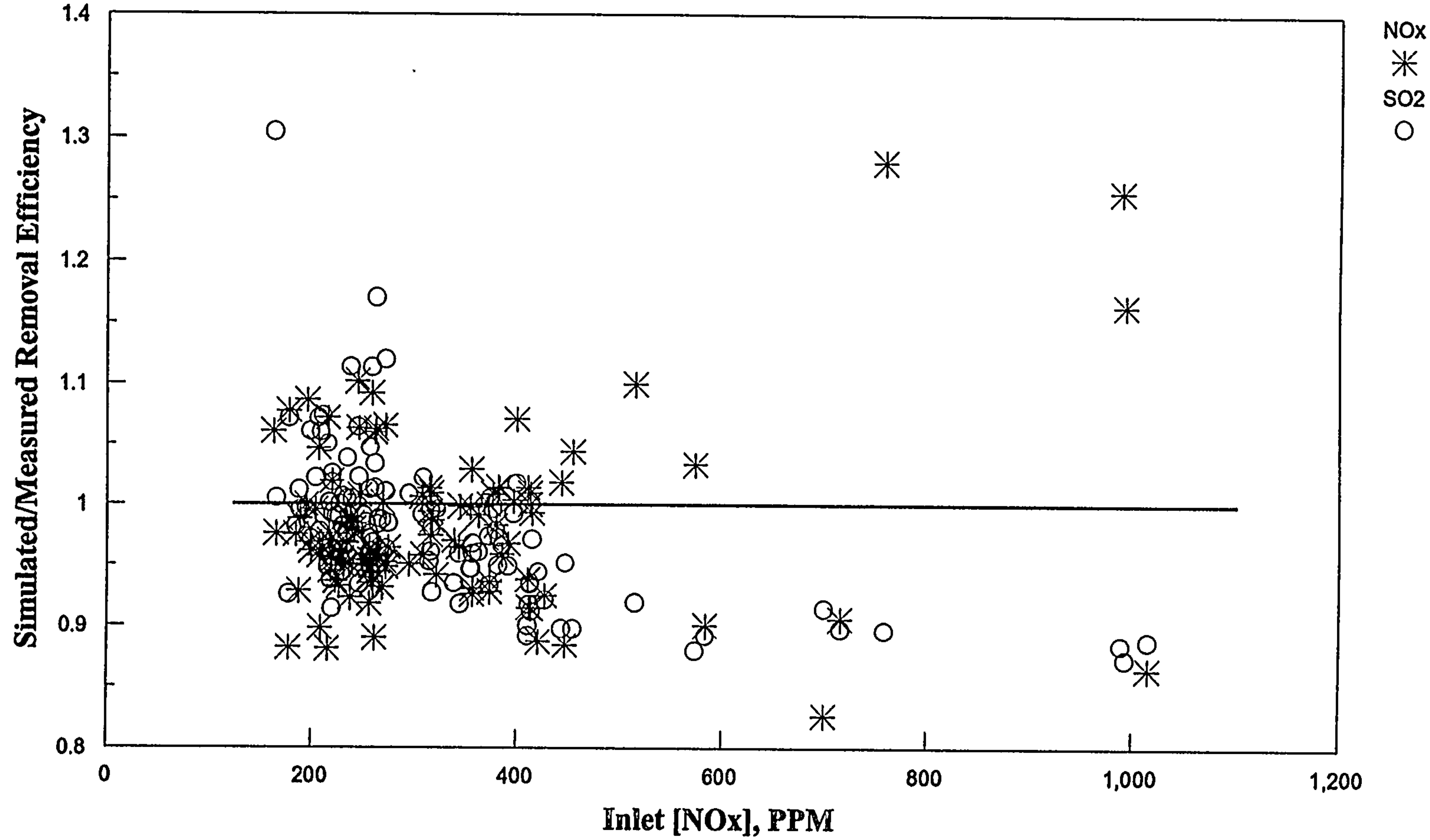

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Figure 3-10. Inlet SO2 Concentration Effect

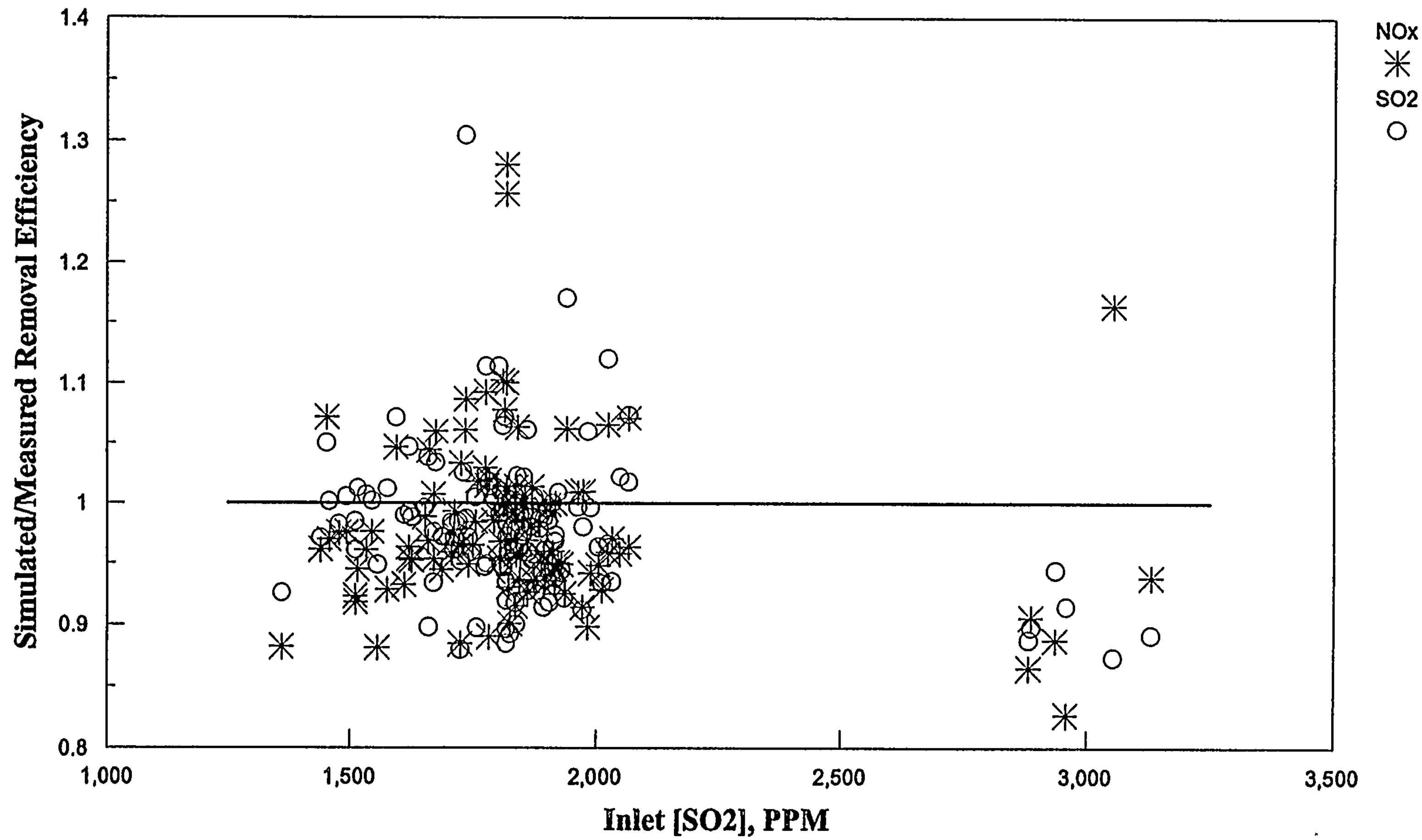

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Figure 3-11. Superficial Gas Velocity Effect

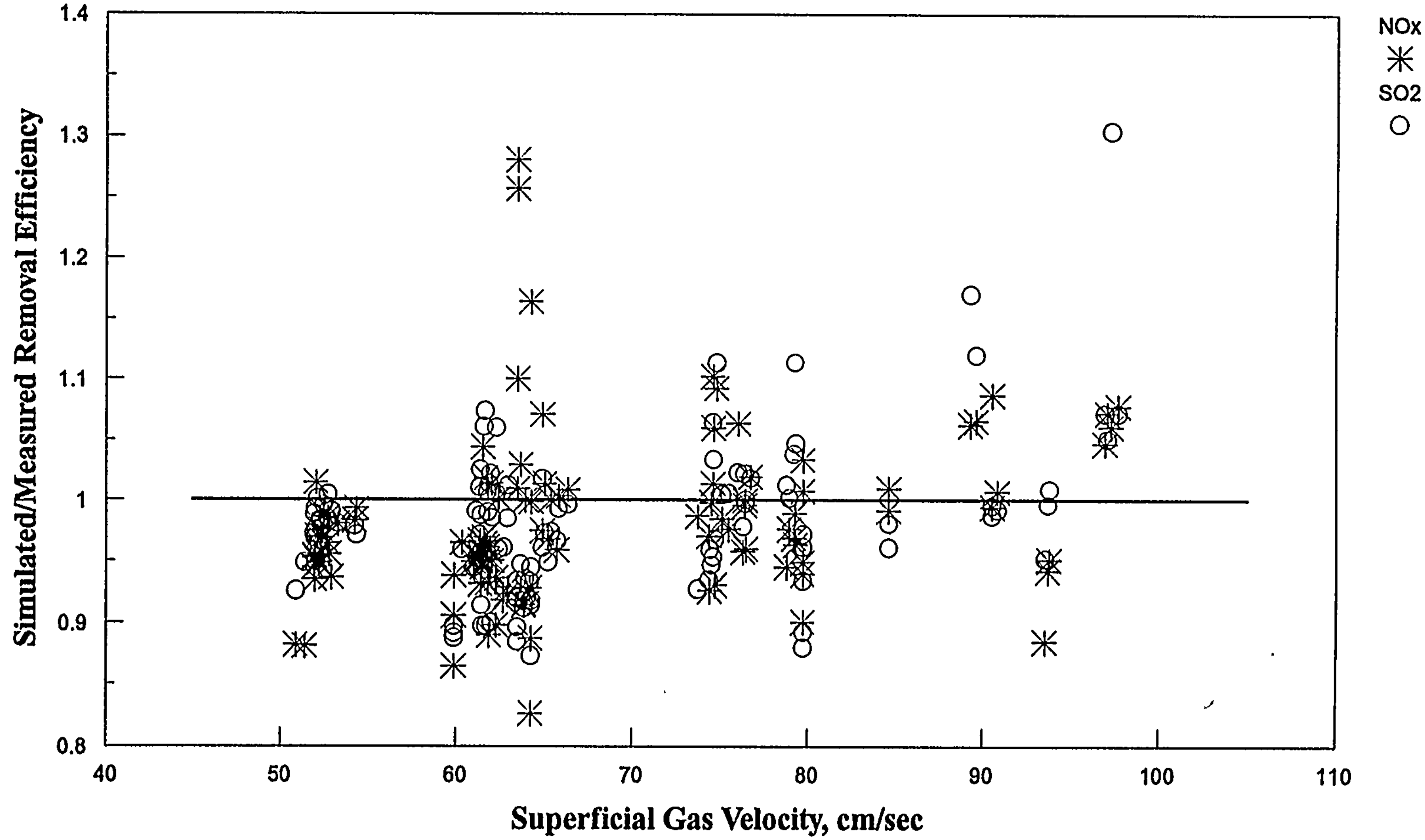

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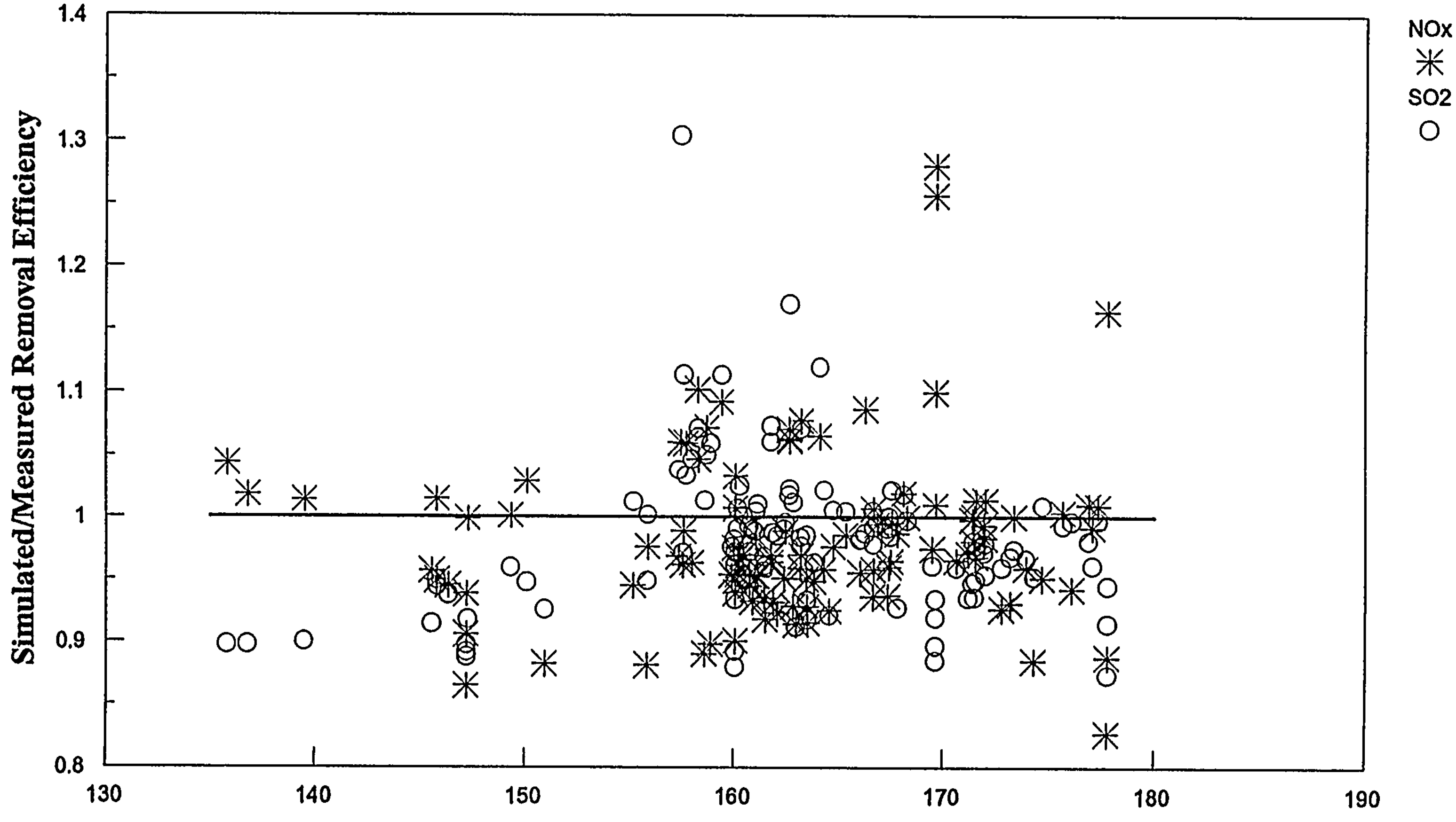
Figure 3-12. Adsorber Temperature Effect



a:q12_3_12.pre

Figure 3-13. Sorbent Residence Time Effect

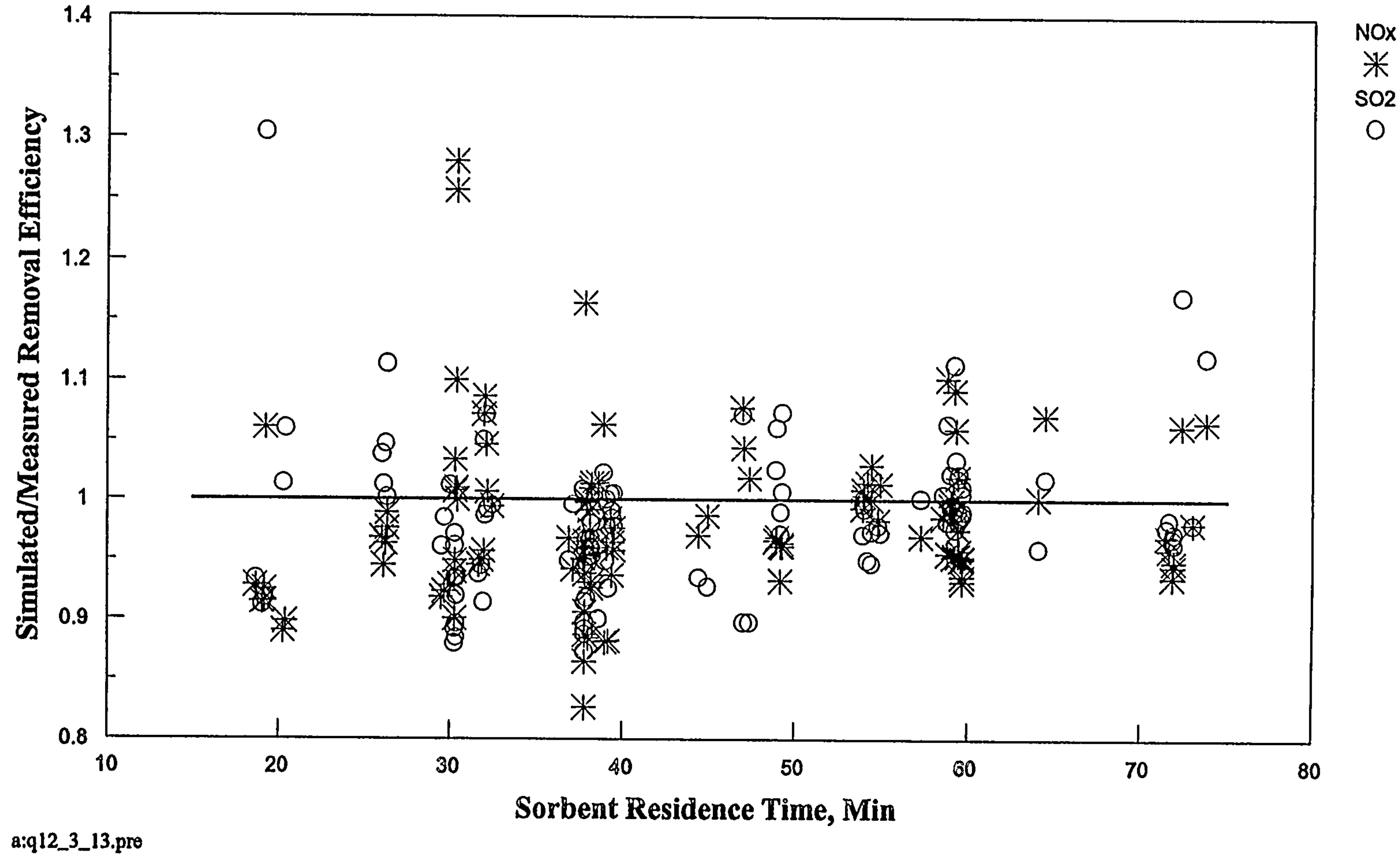


Figure 3-14. Gas-solid Contact Time Effect

(time for gas flow through the settled bed)

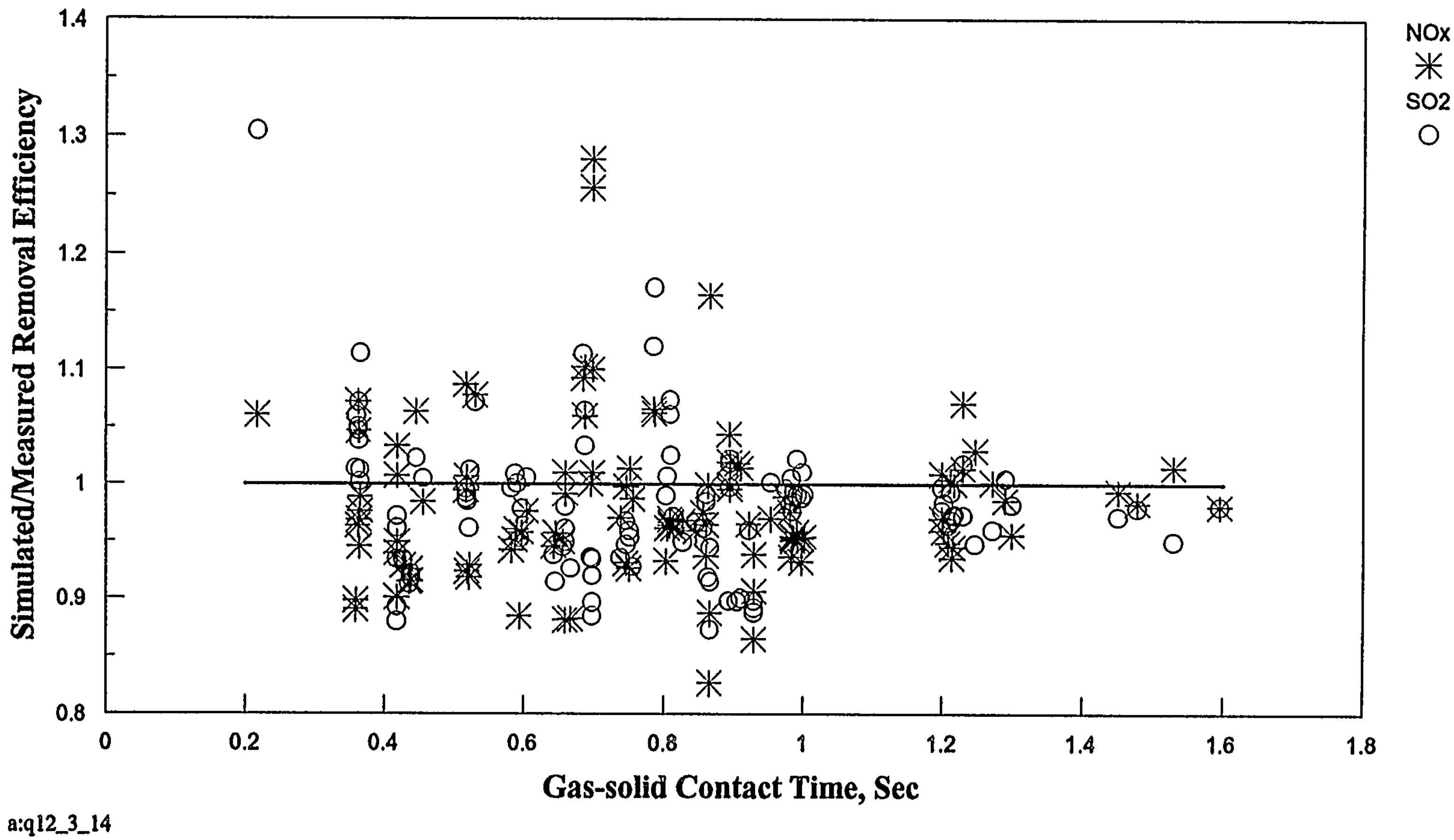
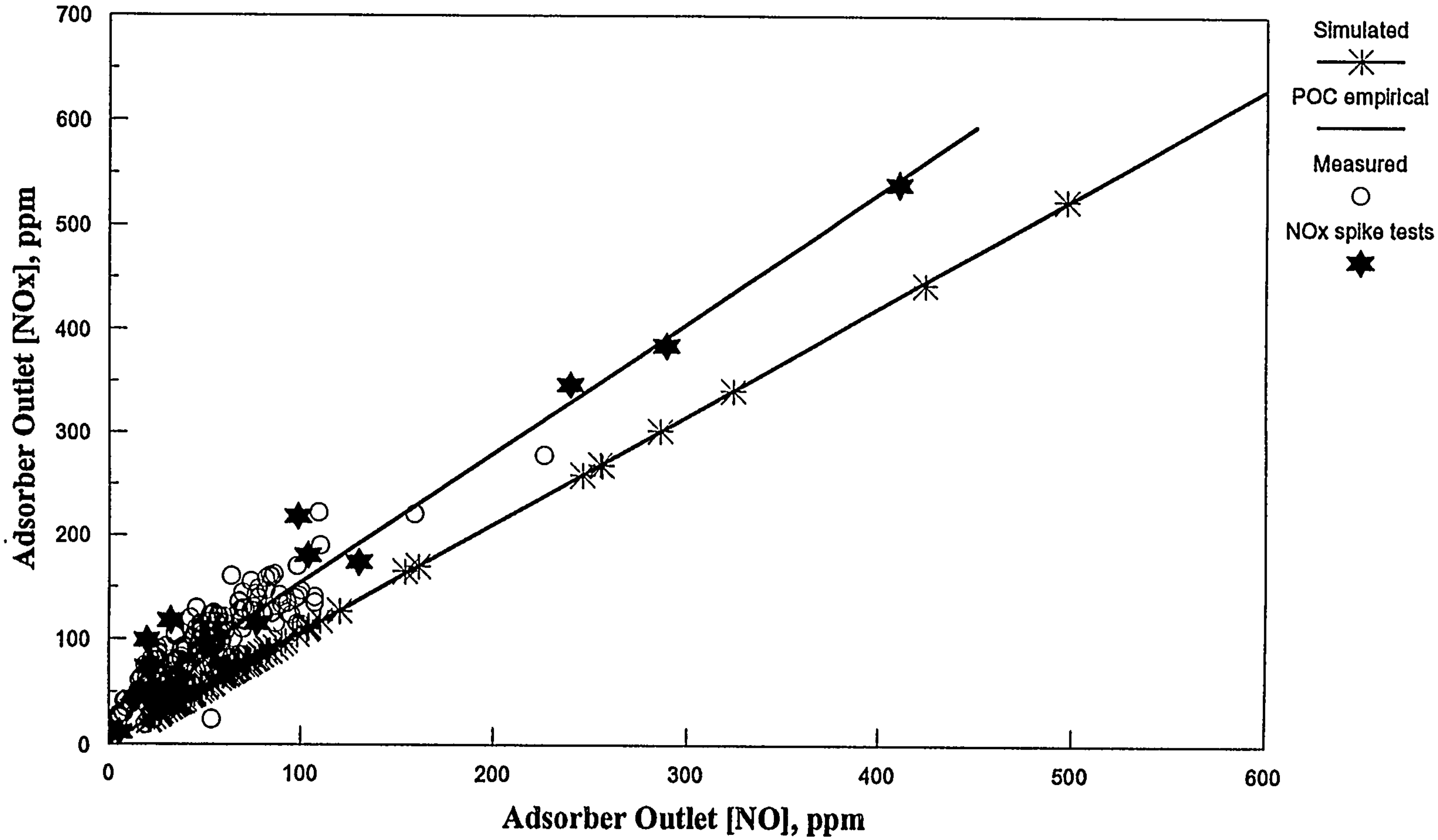


Figure 3-15. POC Adsorber NO and NOx Emission



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To further improve the adsorber model, we need additional laboratory data to assess the NO_2 sorption. Until new laboratory data is available, the adsorption reaction model will remain unchanged. To make the adsorber model more useful, an empirical correlation of the NO_2 emissions from the POC adsorber with its NO_x slip was developed. Combining this empirical correlation with the adsorber model helps the adsorber designer size the vessel and estimate the corresponding NO_2 emissions.

The status of the adsorber model is summarized in the following statements.

1). The program for the adsorber model was developed and tested with the laboratory (2" fixed-bed) and POC (126" fluid-bed) test data.
2). The program requires only one adjustable parameter to scale up the laboratory results to predict the NO_x and SO_2 removal efficiencies for the POC tests.
3). The program fails to predict the NO_2 emissions correctly. But an empirical NO_2 emission correlation was available for the adsorber designer to estimate the NO_2 emissions based on the amount of NO_x slip through the POC adsorber.
4). Improvement of the adsorber model requires more laboratory data. Especially for the NO and NO_2 sorption study.

3.5.3 Process Simulation

As discussed in Section 3.5.1, water adsorption on the sorbent in the sorbent cooler and adsorber and subsequent desorption in the sorbent heater has a measurable effect on the sorbent cooler and sorbent heater energy balances. The primary effect is to increase the gas flow rate through the sorbent cooler/heater train and to increase natural gas consumption in the natural gas fired air heater. The process simulation model code has been modified to include the adsorption/desorption of water onto or off of the sorbent in the appropriate process locations.

3.5.4 Process Economics

Based on Proof-of-Concept construction and operating experience and insight gained during the design of the commercial demonstration unit, a conceptual NOXSO process was developed for a 500 MW coal-fired power plant. A NOXSO Process of this size, or larger, is able to realize economies-of-scale in equipment requirements and construction. The design criteria used in developing the conceptual 500 MW NOXSO Process is shown in Table 3-8. The NOXSO Process would consist of four equal sized modules, each treating the equivalent of 125 MW of flue gas.

The NOXSO Process economic analysis is shown in Table 3-9. The NOXSO Process will reduce SO_2 emissions by 98% to 0.09 lb/mmBtu and reduce NO_x emissions by 85% to 0.12 lb/mmBtu. The total plant cost of the four module NOXSO Process as previously described is estimated at \$115.4 million or approximately \$231/kW. The total plant cost includes the following: land (approximately 65,000 ft^2), escalation during construction, initial catalyst charge, contingency, and all royalties and fees. Working capital was estimated at 3% of the total plant cost plus two months of the net operating costs. The startup expense and organization

Table 3-8. Design Criteria for Economic Analysis

Plant Size, MW	500		
Coal Firing Rate, tph	198	Sulfur in Coal, %	2.8
Coal Heating Value, Btu/lb	12,000	Flue Gas Oxygen Concentration, %	3.0
Net Heat Rate, Btu/kWh	9,500	Flue Gas SO_2 Concentration, ppmd	2,500
Capacity Factor, %	90.0	Flue Gas NO_x Concentration, ppmd	600

was estimated at 2% of the total plant cost. The total capital investment of $123.7 million, or about $247/kW, is the value on which the fixed capital charge will be applied to recover the capital investment.

Fixed and variable operating cost are also shown in Table 3-9. Due to the relative ease of operation, high reliability of the NOXSO Process, and process automation through the use of a distributed computer process control system, it is anticipated that the power plant will not need to employ additional staff to operate the NOXSO system. As such, the operating labor shown is based on 1/2 of a skilled operator and 1/2 of an unskilled operator per shift with the appropriate overhead and supervisory charges applied. Maintenance materials and labor is estimated at $1.2 million per year. Maintenance requirements are based on pilot plant operating experience and accepted industry equipment maintenance requirements. The general and administrative expense was estimated at 2% of the total plant cost. The total plant fixed operating cost is $3.8 million per year, or about 1 mill/kWh.

The gross variable operating costs, $12.9 million per year, or approximately 3.3 mills/kWh, were estimated at a 90% plant capacity factor and the unit rates shown. Including the revenue from the sale of elemental sulfur, $1.7 million/year, the net operating and maintenance (O&M) cost of the NOXSO system designed for a 500 MW power plant burning 2.8% sulfur coal is $15.0 million, or approximately 3.8 mills/kWh.

Table 3-9. NOXSO Process Economic Analysis (1)

PLANT INFORMATION		
Power Plant Gross MW	500	
Capacity Factor	0.90	
Number of NOXSO Modules	4	
Heat Rate, BTU/kWh	9,500	
Coal Heating Value, BTU/lb	12,000	
Coal Sulfur, %	2.80	
NOx Loading, lb/mmBTU	0.80	
NOXSO PROCESS REMOVAL EFFICIENCIES		
SO2	98.0	
NOx	85.0	
EMISSIONS DATA, tpy		
Uncontrolled SO2	87,291	
Controlled SO2	1,747	
Phase I SO2 Limit (2)	46,811	
Uncontrolled NOx	15,051	
Controlled NOx	2,262	
CAPITAL COST, $		
Total Plant Cost (3)	115,400,000	
Working Capital (4)	5,963,000	
Startup Expense and Organization (5)	2,308,000	
Total Capital Investment	**123,671,000**	
$/kW	**247**	
OPERATING AND MAINTENANCE COSTS		
Economic Parameters		
Electricity, $/kWh	0.018	
Natural Gas, $/mmBTU	2.50	
NOXSO Sorbent, $/lb	1.50	
Water, $/kgal	0.6	
Net Sulfur Value, $/ton	40	
Fixed Charge Rate, % (6)	10.6	
NOx Value, $/ton (7)	800	
Fixed Operating Cost	**($/year)**	**(mills/kWh)**
Operating Labor (8)	306,000	0.08
Maintenance Materials & Labor (9)	1,191,000	0.30
G & A (5)	2,308,000	0.59
Total Fixed Operating Cost	**3,805,000**	**0.97**
Variable Operating Cost		
Water	112,000	0.03
Claus Catalyst	74,000	0.02
Natural Gas	6,273,000	1.59
Sorbent	5,296,000	1.34
Net Electricity	1,161,000	0.29
Total Variable Operating Cost	**12,916,000**	**3.28**
GROSS OPERATING AND MAINTENANCE COST	**16,721,000**	**4.24**
SULFUR	**(1,714,000)**	**(0.43)**
NET OPERATING AND MAINTENANCE COST	**15,007,000**	**3.81**

Table 3-9. NOXSO Process Economic Analysis (1) continued

CONSTANT DOLLAR LEVELIZED COST WITH SULFUR PLANT REVENUE

$/yr (10)	28,116,000
mills/kWh	7.1
$/ton SO2 with NOx Credit	209
$/ton NOx	800

CONSTANT DOLLAR LEVELIZED COST WITH SULFUR PLANT AND SO2 EMISSION ALLOWANCE REVENUE

Phase I Allowances	
Phase I Emission Limit	46,811
SO2 Emissions with NOXSO	1,747
Excess Allowances Generated @ $300	$13,519,000
Net Levelized Cost	
$/yr (11)	14,597,000
mills/kWh	3.7
$/ton SO2 with NOx Credit	51
$/ton NOx	800

(1) 1993 Dollars
(2) 2.5 lb SO2/mmBTU
(3) Includes the following: initial catalyst charge, engineering and home office fees, royalties, escalation during construction, contingency, G&A, and constructor's fee.
(4) 3% of Total Plant Cost + 2 months Net Operating Expenses.
(5) 2% of Total Plant Cost.
(6) Fixed Charge Rate based on 30 year book life, 20 year tax life, 38% composite Federal and State tax, and 2% for property taxes and insurance.
(7) Conservative cost of NOx removal based on SCR technology.
(8) 1/2 skilled operator per shift, 1/2 unskilled operator per shift.
(9) Estimate based on pilot plant experience and expected life of equipment.
(10) Total Capital Investment x Fixed Charge Rate + O&M Costs - Sulfur Value.
(11) Total Capital Investment x Fixed Charge Rate + O&M Costs - Sulfur Value - SO2 Allowance

A sensitivity analysis was performed to determine the effect of the net sale price of sulfur, the unit cost of natural gas and sorbent, and the energy credit on the net operating and maintenance cost. The results are shown in Figure 3-16. The baseline O&M is 3.8 mills/kWh and, as can be seen, large variations in the studied parameters do not significantly impact the net O&M cost. If sulfur is disposed at a zero net profit the operating cost will only increase to 4.24 mills/kWh. The price of natural gas can increase to $3.50/mmBTU producing a small increase in the net O&M cost from the baseline of 3.81 to 4.44 mills/kWh. The O&M cost will increase by 0.9 to 4.7 mills/kWh if the unit cost of the NOXSO sorbent increases by $1.00 to $2.50/lb. If, assuming additional power can not be generated by the power plant due to integration with the NOXSO Process the net O&M will increase from 3.81 to 4.14 mills/kWh. This assumes no credit was given for the resulting reduction in power plant coal feed rate.

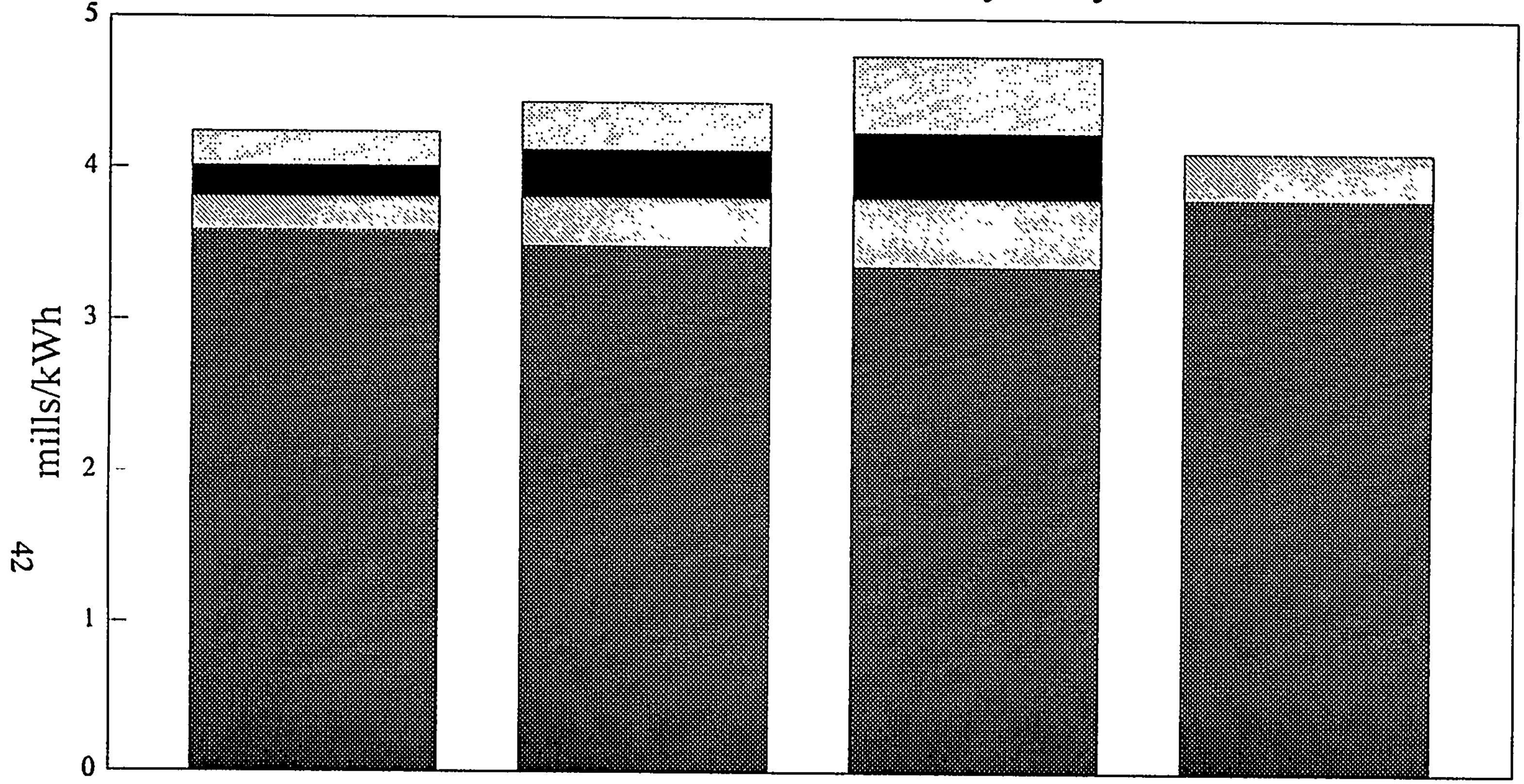
On a constant 1993 dollar basis, i.e. no inflation applied to the variable operating costs, applying the fixed charge rate of 10.6% to the total capital investment and including the sulfur revenue, the levelized cost is $28.2 million, or about 7.1 mills/kWh. The fixed charge rate is an EPRI generated value based on a 30-year book life, 20 year tax life, and a 38% composite federal and state tax rate[3]. It also includes 2% for insurance. Neglecting the value of NO_x removal, the levelized cost of the NOXSO system in terms of $/ton SO_2 removed would be very competitive at $329/ton removed. However, the NOXSO system is an integrated process which simultaneously removes SO_2 and NO_x and thus it is impossible to separate the cost of removing the SO_2 from the cost of removing NO_x. Assigning a value of $800/ton of NO_x removed yields an SO_2 removal cost of $209/ton which is superior to current FGD costs of $350-600/ton[4]. The value of $800/ton assigned to NO_x removal is based upon costs for high efficiency SCR processes. This is a conservative number, as SCR costs are typically higher. In addition, a range of cost effectiveness for NO_x control is cited at $570-$1,500/ton removed under several states Reasonably Available Control Technology (RACT) criteria.

It is also appropriate to consider over compliance since the high efficiency of the NOXSO Process will allow a utility to generate SO_2 allowances which can be sold to partially offset the operating cost. The "Phase I SO_2 limit" in Table 3-9 is calculated based on allowable emissions of 2.5 lb SO_2/mmBTU. Beginning with Phase II in the year 2000 the number of allowances generated will decrease; however, it is also likely that the value of allowances will increase significantly, offsetting to some degree the reduction in allowances generated. Based on the above assumptions, $13.5 million would be generated by the sale of SO_2 allowances offsetting the operating costs and reducing the levelized cost to $14.5 million, or about 3.7 mills/kWh. The cost of SO_2 removal with the credit for NO_x removal decreases to $51/ton. Table 3-10 presents the utility and raw materials consumption for the four module NOXSO system based on the design criteria as given in Table 3-8.

3.6 Plant Characterization

Plant characterization activities are on hold until a new host site is identified.

Figure 3-16. O & M Sensitivity Analysis



Sulfur
$0/ton
$20/ton
$40/ton
$60/ton

Natural Gas
$3.50/mmBTU
$3.00/mmBTU
$2.50/mmBTU
$2.00/mmBTU

Sorbent
$2.50/lb
$2.00/lb
$1.50/lb
$1.00/lb

Energy Credit
None
100%

Table 3-10. Raw Material and Utility Consumption

NATURAL GAS, lb/hr		
Air Heater	6,152	
Regeneration	3,644	
Sulfur Plant	3,344	
Total Natural Gas	**13,140**	
SORBENT MAKEUP RATE, lb/hr	**448**	
STEAM, lb/hr		
Gross Claus Plant Steam Production	81,608	
NOXSO Process Steam Consumption	(39,252)	
Net Claus Plant Steam Production	**42,356**	
WATER, gpm	**387**	
ELECTRICAL POWER CONSUMPTION	**(kW)**	**Gross Power (%)**
Flue Gas Booster Fans	8,824	1.8
Sorbent Cooler/Heater Fans	2,748	0.5
Claus Plant	936	0.2
Air Compressors	3,104	0.6
Miscellaneous	1,332	0.3
Gross Electrical Power Consumption	16,944	3.4
Less Energy Credits		
FD Fan Credit	200	0.0
NOx Recycle Credit	4,032	0.8
Claus Steam Credit	3,446	0.7
Combustion Air Steam Preheat Credit	1,056	0.2
Total Energy Credits	8,734	1.7
Net Electrical Power Consumption	**8,210**	**1.7**

3.7 Site Survey/Geotechnical Investigation

Site survey/geotechnical investigation activities are on hold until a new host site is identified.

3.8 Permitting

Permitting activities are on hold until a new host site is identified.

4 PLANS FOR NEXT QUARTER

The main priority for next quarter is the evaluation and selection of a host site for the project. It is essential that a technically acceptable site be selected so the process can be properly demonstrated.

Immediately upon identification of the host site, work will begin to modify the EIV with information specific to the new site. It is critical to satisfy the NEPA requirements as soon as possible to prevent delaying the project.

The adsorber pressure vessel design procedure will be modified to be used for design of the high temperature, tapered sorbent heater and sorbent cooler vessels.

The need to perform additional NO_x destruction studies will be evaluated based on the boiler type for the new host site. If required, these studies could take the form of scaled experiments or computer modelling.

Demolition of the pilot plant will be completed this quarter. All equipment which can be reused at the commercial plant will be removed and placed in storage.

The fluid-bed adsorber computer model will be modified to allow analysis of multi-stage fluid-bed adsorbers. Using this model, the optimum number of adsorber stages will be determined. Additionally, work on the regenerator model will begin. Because the regeneration is much more complicated than adsorption, it is expected development of this model and conducting necessary laboratory experiments will require more time and effort than the adsorption model.

The NOXSO process simulation model will continue to be updated and developed to more accurately simulate the operation of the NOXSO process. A version of the simulation model will be developed to model off design cases. For example, how will various process parameters of a NOXSO process designed for flue gas containing 2500 ppm of SO_2 be affected when the system is operating on flue gas containing 1250 ppm of SO_2.

Tests will be conducted in the laboratory to determine the sorbent's capacity for adsorbing water at typical adsorber temperatures and flue gas water contents.

As soon as a new host site is identified, activities to collect specific plant information, collect site and geotechnical information, and identify necessary permits will be initiated.

5 REFERENCES

1. Models for Flow Systems and Chemical Reactors, p.369, 1975.

2. "Reactant Dynamics in Catalytic Fluidized Bed Reactors with Flow Reversal of Gas in the Emulsion Phase", Chemical Engineering Science, vol. 37, no. 4, P.553, 1982.

3. Electronic Power Research Institute (EPRI) Study of Processes for Combined SO_x/NO_x Control, 1990.

4. EPRI 1990 Update of FGD Economic Evaluations.

APPENDIX I

ADSORBER GENERAL DATA

NOXSO CORPORATION
ASME BOILER AND PRESSURE VESSEL CODE
SECTION VIII DIVISION 1

JOB: DEMONSTRATION PLANT

ADSORBER
GENERAL DATA

	INTERNAL		EXTERNAL
DESIGN PRESSURE	3.50 PSI		0.18 PSI
DESIGN TEMPERATURE	400.00 DEG F		400.00 DEG F
CORR. ALLOWANCE	0.125 IN	RADIOGRAPHY:	SPOT
POST WELD HEAT TREATMENT:	NO	JOINT EFF.	0.85
SORBENT : DEPTH	3.00 FT	DENSITY	35.00 LBM/FT^3

MATERIALS OF CONSTRUCTION

	DESIGNATION	ALLOWABLE STRESS
SHELL	SA−516 GR 70	17500 PSI
TOP HEAD	SA−516 GR 70	17500 PSI
BOTTOM HEAD	SA−516 GR 70	17500 PSI
ROLLED NOZZLES	SA−516 GR 70	17500 PSI
PIPE NOZZLES	SA−106 B	15000 PSI
FLANGES	SA−105	17500 PSI
STUD BOLTS	SA−193 GR B7	20000 PSI
VACUUM STIFFENERS	SA−36	14500 PSI
SKIRT	SA−36	12700 PSI

DIMENSIONAL DATA

DIAMETER	516 IN	RADIUS	258 IN
LENGTH, TAN. TO TAN.	280 IN	HEAD DEPTH	129 IN

CALCULATIONS

CYLINDRICAL SHELL

PARAGRAPH UG−27 THICKNESS OF SHELLS UNDER INTERNAL PRESSURE

CIRCUMFERENTIAL STRESS − t=P*R/(S*E−0.6*P) = 0.061 IN

PARAGRAPH UG−28 THICKNESS OF SHELLS UNDER EXTERNAL PRESSURE

Number of vacuum stiffeners −		=	0
Distance between lines of support −		L=	366 IN
Do/t=	2040	L/D=	0.709
E =	2.77E+07 PSI		

FROM EQUATIONS ONLY − see "THEORY AND DESIGN OF PRESSURE VESSELS" by Harvey section 8.5 page 606.

Required thickness for external pressure − t=D*(3*L*Pa/(2.6*D*E))^0.4= 0.253 IN

FROM EQUATIONS AND VACUUM CHARTS

A =	0.00000	B=	0

ALLOWABLE EXTERNAL PRESSURE−Pa=4*B/(3*D/t) = 0.000 PSI

OR

ALLOWABLE EXTERNAL PRESSURE−Pa=2*A*E/(3*D/t) = 0.000 PSI

PARAGRAPH UG−29 STIFFENING RINGS FOR CYLINDRICAL SHELLS UNDER EXTERNAL PRESSURE

STIFFENER − T−SECTION

FLANGE	− W =	8.030 IN	t=	0.493 IN
WEB	− H =	3.567 IN	t=	0.315 IN
AREA	− As =	5.082 IN^2		
NEUTRAL AXIS − C1=		0.695 IN	C2=	3.365 IN
SECTION MOMENT OF INERTIA −			I=	4.878 IN^4

STIFFENER AND VESSEL WALL COMBINED

WIDTH OF WALL PERMITTED AS STIFFENER =1.1*SQRT(D*ts) = 12.566 IN

AREA − WALL	A =	3.178 IN^2	TOTAL A =	8.26 IN^2
NEUTRAL AXIS − C1=		1.990 IN	C2=	2.070 IN

COMBINED SECTION AND VESSEL MOMENT OF INERTIA − I = 27.02 IN^4

REQUIRED MOMENT OF INERTIA OF COMBINED SECTION AND VESSEL

B=0.75*P*D/(t+As/L) = 5016 A=2*B/E = 0.00036

REQ'D MOMENT OF INERTIA − I=(D^2*Ls*(ts+As/Ls)*A)/10.9 = 44.97 IN^4

PARAGRAPH UG−23 MAXIMUM ALLOWABLE STRESS VALUES

(b) Maximum allowable longitudinal compressive stress shall be the lesser of the allowable tensile stress or the value of B.

(d) For the combination of earthquake loading or wind loading with other loads the allowable stress found in (b) can be increased by 20%.

COMPRESSIVE LOADS − DENSITY SORB. * DEPTH * AREA * NO. BEDS + STRUCTURE WEIGHT
+ VESSEL WEIGHT = 556241 LB

Required thickness for compressive load −	t=	0.207 IN
Required outside radius of shell −	Ro=	258.268 IN
Stress due to compressive load −	S=	1657 PSI

A = 0.125/(Ro/t) = 1.00E−04 B=1.2*A*E/2= 1665 PSI

Bending moment due to wind load − M= 356461 FT−LB

Required thickness for wind load −

t = M/(PI*R^2*Sa*E) = 0.012 IN

Bending moment due to earthquake load –	M=	1041537 FT–LB
Required thickness for earthquake load –		
t = M/(PI*R^2*Sa*E) =		0.036 IN
Total required thickness for combined loads	– t=	0.496 IN
Total required thickness for combined loads plus corrosion allowance	– t=	0.621 IN
Actual thickness for combined loads plus corrosion allowance	– t=	0.625 IN
Weight of cylindrical shell –	Ws =	79999 LB

ELLIPSOIDAL HEADS

TOP HEAD

PARAGRAPH UG–32 FORMED HEADS, AND SECTIONS, PRESSURE ON CONCAVE SIDE

(d) An acceptable approximation of a 2:1 ellipsodial head is knuckle radius 0.17*D and spherical radius 0.90*D.

t = P*D/(2*S*E–0.2*P) = 0.061 IN

PARAGRAPH UG–33 FORMED HEADS, AND SECTIONS, PRESSURE ON CONVEX SIDE

(d)

Required thickness for external pressure – t= 0.061 IN

FROM EQUATIONS AND VACUUM CHARTS

A = 0.125/(Ro/t) = 0.00003 B= 0

ALLOWABLE EXTERNAL PRESSURE–Pa=4*B/(3*Do/t) = 0.000 PSI

OR

ALLOWABLE EXTERNAL PRESSURE–Pa=2*A*E/(3*Do/t) = 0.266 PSI

Minimum straight flange thickness –	t=	0.496 IN
Minimum straight flange thickness plus corrosion allowance–	t=	0.625 IN
Maximum formed section thinout –	t=	0.063 IN
Minimum required formed section thickness –	t=	0.433 IN
Minimum required formed section thickness plus corrosion allowance	–t=	0.563 IN
Weight of 2:1 elliptical top head –	Wth =	66342 LB

BOTTOM HEAD

PARAGRAPH UG–32 FORMED HEADS, AND SECTIONS, PRESSURE ON CONCAVE SIDE

(d) An acceptable approximation of a 2:1 ellipsodial head is knuckle radius 0.17*D and spherical radius 0.90*D.

t = P*D/(2*S*E–0.2*P) = 0.061 IN

PARAGRAPH UG−33 FORMED HEADS, AND SECTIONS, PRESSURE ON CONVEX SIDE
(d)

Required thickness for external pressure − t= 0.061 IN

FROM EQUATIONS AND VACUUM CHARTS

A = 0.125/(Ro/t)	=	0.00003	B=	0
ALLOWABLE EXTERNAL PRESSURE−Pa=4*B/(3*Do/t)			=	0.000 PSI
OR				
ALLOWABLE EXTERNAL PRESSURE−Pa=2*A*E/(3*Do/t)			=	0.266 PSI

Minimum straight flange thickness −	t=	0.496 IN
Minimum straight flange thickness plus corrosion allowance−	t=	0.625 IN
Maximum formed section thinout −	t=	0.063 IN
Minimum required formed section thickness −	t=	0.433 IN
Minimum required formed section thickness plus corrosion allowance −	t=	0.563 IN

Weight of 2:1 elliptical bottom head − Wth = 66342 LB

FLUE GAS INLET NOZZLE

DIAMETER	120 IN	RADIUS	60 IN
LENGTH	12 IN		

PARAGRAPH UG−27 THICKNESS OF SHELLS UNDER INTERNAL PRESSURE

CIRCUMFERENTIAL STRESS − t=P*R/(S*E−0.6*P) = 0.014 IN

PARAGRAPH UG−28 THICKNESS OF SHELLS UNDER EXTERNAL PRESSURE

Do/t=	4467	L/D=	0.100
E =	2.77E+07 PSI		

FROM EQUATIONS ONLY − see "THEORY AND DESIGN OF PRESSURE VESSELS" by Harvey section 8.5 page 606.

Required thickness for external pressure − t=D*(3*L*Pa/(2.6*D*E))^0.4= 0.027 IN

FROM EQUATIONS AND VACUUM CHARTS

A =	0.00000	B=	0

ALLOWABLE EXTERNAL PRESSURE−Pa=4*B/(3*D/t) = 0.000 PSI

OR

ALLOWABLE EXTERNAL PRESSURE−Pa=2*A*E/(3*D/t) = 0.000 PSI

Minimum nozzle thickness	t=	0.250 IN
Minimum nozzle thickness plus corrosion allowance	t=	0.375 IN

FLUE GAS OUTLET NOZZLE

DIAMETER	120 IN	RADIUS	60 IN
LENGTH	12 IN		

PARAGRAPH UG−27 THICKNESS OF SHELLS UNDER INTERNAL PRESSURE

CIRCUMFERENTIAL STRESS − t=P*R/(S*E−0.6*P) = 0.014 IN

PARAGRAPH UG−28 THICKNESS OF SHELLS UNDER EXTERNAL PRESSURE

Do/t=	4467	L/D=	0.100
E =	2.77E+07 PSI		

FROM EQUATIONS ONLY − see "THEORY AND DESIGN OF PRESSURE VESSELS" by Harvey section 8.5 page 606.

Required thickness for external pressure − t=D*(3*L*Pa/(2.6*D*E))^0.4= 0.027 IN

FROM EQUATIONS AND VACUUM CHARTS

A =	0.00000	B=	0

ALLOWABLE EXTERNAL PRESSURE−Pa=4*B/(3*D/t) = 0.000 PSI

OR

ALLOWABLE EXTERNAL PRESSURE−Pa=2*A*E/(3*D/t) = 0.000 PSI

Minimum nozzle thickness	t=	0.250 IN
Minimum nozzle thickness plus corrosion allowance	t=	0.375 IN

MANWAYS

DIAMETER	24 IN	RADIUS	12 IN
LENGTH	12 IN		

PARAGRAPH UG−27 THICKNESS OF SHELLS UNDER INTERNAL PRESSURE

CIRCUMFERENTIAL STRESS − t=P*R/(S*E−0.6*P) = 0.003 IN

PARAGRAPH UG−28 THICKNESS OF SHELLS UNDER EXTERNAL PRESSURE

Do/t=	2347	L/D=	0.500
E =	2.77E+07 PSI		

FROM EQUATIONS ONLY − see "THEORY AND DESIGN OF PRESSURE VESSELS" by Harvey section 8.5 page 606.

Required thickness for external pressure − t=D*(3*L*Pa/(2.6*D*E))^0.4= 0.010 IN

FROM EQUATIONS AND VACUUM CHARTS

A =	0.00000	B=	0

ALLOWABLE EXTERNAL PRESSURE−Pa=4*B/(3*D/t) = 0.000 PSI

OR

ALLOWABLE EXTERNAL PRESSURE−Pa=2*A*E/(3*D/t) = 0.000 PSI

Minimum nozzle thickness	t=	0.375 IN
Minimum nozzle thickness plus corrosion allowance	t=	0.500 IN

FLUE GAS INLET NOZZLE

PARAGRAPH UG−37 REINFORCEMENT REQUIRED FOR OPENINGS IN SHELLS AND FORMED HEADS
For internal pressure tr and trn are the values required for the internal design pressure.

Required area

A =d*tr*F+2*tn*tr*F*(1−fr1) = 7.28 IN^2

Area available in head; use larger value −

A1=d*(E1*t−F*tr)−2*tn*(E1*t−F*tr)*(1−fr1) = 36.91 IN^2

or

A1=2*(t+tn)*(E1*t−F*tr)−2*tn*(E1*t−F*tr)*(1−fr1) = 0.420 IN^2

Area available in nozzle projecting outward; use smaller value −

A2=5*(tn−trn)*fr2*t = 0.511 IN^2

or

A2=5*(tn−trn)*fr2*tn = 0.295 IN^2

Area available in nozzle projecting inward −

A3=2*(tn−c)*fr2*h = 0.156 IN^2

Area available in nozzle projecting outward weld –

A41=(leg)^2*fr2	=	0.063 IN^2

Area available in nozzle projecting inward weld –

A43=(leg)^2*fr2	=	0.063 IN^2

Total area available for reinforcement –

A1+A2+A3+A41+A43	=	37.49 IN^2

For external pressure tr and trn are the values required for the external design pressure.

Required area

A =(d*tr*F+2*tn*tr*F*(1–fr1))/2	=	3.64 IN^2

Area available in head; use larger value –

A1=d*(E1*t–F*tr)–2*tn*(E1*t–F*tr)*(1–fr1)	=	36.91 IN^2
A1=2*(t+tn)*(E1*t–F*tr)–2*tn*(E1*t–F*tr)*(1–fr1)	=	0.420 IN^2

Area available in nozzle projecting outward; use smaller value –

A2=5*(tn–trn)*fr2*t	=	0.483 IN^2
A2=5*(tn–trn)*fr2*tn	=	0.279 IN^2

Area available in nozzle projecting inward –

A3=2*(tn–c)*fr2*h	=	0.156 IN^2

Area available in nozzle projecting outward weld –

A41=(leg)^2*fr2	=	0.063 IN^2

Area available in nozzle projecting inward weld –

A43=(leg)^2*fr2	=	0.063 IN^2

Total area available for reinforcement –

A1+A2+A3+A41+A43	=	37.47 IN^2

PARAGRAPH UW–16 MINIMUM REQUIREMENTS FOR ATTACHMENT WELDS AT OPENINGS
(d) Neck Attached by Fillet or Partial Penetration Welds. Figure 16.1 (i).

Throat of welds t1 and t2 shall not be less than the smaller of 1/4" or .7 tmin.
and t1 + t2 must be greater than or equal to 1.25 tmin.

tmin=lesser of 3/4", t or tn	=	0.250 IN
t1=t2	=	0.175 IN
1.25*tmin	=	0.313 IN
t1+t2	=	0.350 IN
Minimum leg of weld	=	0.250 IN

PARAGRAPH UG–41 STRENGTH OF REINFORCEMENT
(b)

(1) W 1–1=(A2+A41)*S	=	6254 LB
W 2–2=(A2+A3+A41+A43+2*tn*t*fr1)*S	=	13873 LB
(2) W =(A–(d–2*tn)*(E1*t–F*tr))*S	=	–515778 LB

PARAGRAPH UG−45 NOZZLE NECK THICKNESS

(c) Allowable stress in shear for nozzle neck	=	12250	PSI

PARAGRAPH UW−15 WELDED CONNECTIONS

(c) Allowable stress in shear for fillet weld	=	8575	PSI

Strength of connection elements:

Nozzle wall shear=PI/2*davg.*tn*Sa	=	578470	LB
Fillet weld shear=PI/2*dout.*leg*Sa	=	405771	LB

Strength paths:

1−1= Nozzle wall shear + Fillet weld shear	=	984241	LB
2−2= Inner+ Outer Fillet weld shear	=	811542	LB

FLUE GAS OUTLET NOZZLE

PARAGRAPH UG−37 REINFORCEMENT REQUIRED FOR OPENINGS IN SHELLS AND FORMED HEADS
For internal pressure tr and trn are the values required for the internal design pressure.

Required area

A =d*tr*F+2*tn*tr*F*(1−fr1)	=	7.28	IN^2

Area available in shell; use larger value −

A1=d*(E1*t−F*tr)−2*tn*(E1*t−F*tr)*(1−fr1)	=	36.91	IN^2
or			
A1=2*(t+tn)*(E1*t−F*tr)−2*tn*(E1*t−F*tr)*(1−fr1)	=	0.420	IN^2

Area available in nozzle projecting outward; use smaller value −

A2=5*(tn−trn)*fr2*t	=	0.511	IN^2
or			
A2=5*(tn−trn)*fr2*tn	=	0.295	IN^2

Area available in nozzle projecting inward −

A3=2*(tn−c)*fr2*h	=	0.156	IN^2

Area available in nozzle projecting outward weld −

A41=(leg)^2*fr2	=	0.063	IN^2

Area available in nozzle projecting inward weld −

A43=(leg)^2*fr2	=	0.063	IN^2

Total area available for reinforcement −

A1+A2+A3+A41+A43	=	37.49	IN^2

For external pressure tr and trn are the values required for the external design pressure.

Required area

A =(d*tr*F+2*tn*tr*F*(1−fr1))/2	=	3.64	IN^2

Area available in shell; use larger value –

A1=d*(E1*t–F*tr)–2*tn*(E1*t–F*tr)*(1–fr1)	=	36.91 IN^2
or		
A1=2*(t+tn)*(E1*t–F*tr)–2*tn*(E1*t–F*tr)*(1–fr1)	=	0.420 IN^2

Area available in nozzle projecting outward; use smaller value –

A2=5*(tn–trn)*fr2*t	=	0.483 IN^2
or		
A2=5*(tn–trn)*fr2*tn	=	0.279 IN^2

Area available in nozzle projecting inward –

A3=2*(tn–c)*fr2*h	=	0.156 IN^2

Area available in nozzle projecting outward weld –

A41=(leg)^2*fr2	=	0.063 IN^2

Area available in nozzle projecting inward weld –

A43=(leg)^2*fr2	=	0.063 IN^2

Total area available for reinforcement –

A1+A2+A3+A41+A43	=	37.47 IN^2

PARAGRAPH UW–16 MINIMUM REQUIREMENTS FOR ATTACHMENT WELDS AT OPENINGS

(d) Neck Attached by Fillet or Partial Penetration Welds. Figure 16.1 (i).

Throat of welds t1 and t2 shall not be less than the smaller of 1/4" or .7 tmin. and t1 + t2 must be greater than or equal to 1.25 tmin.

tmin=lesser of 3/4", t or tn	=	0.250 IN
t1=t2	=	0.175 IN
1.25*tmin	=	0.313 IN
t1+t2	=	0.350 IN
Minimum leg of weld	=	0.250 IN

PARAGRAPH UG–41 STRENGTH OF REINFORCEMENT

(b)

(1) W 1–1=(A2+A41)*S	=	6254 LB
W-2–2=(A2+A3+A41+A43+2*tn*t*fr1)*S	=	13873 LB
(2) W =(A–(d–2*tn)*(E1*t–F*tr))*S	=	–515778 LB

PARAGRAPH UG–45 NOZZLE NECK THICKNESS

(c) Allowable stress in shear for nozzle neck = 12250 PSI

PARAGRAPH UW–15 WELDED CONNECTIONS

(c) Allowable stress in shear for fillet weld = 8575 PSI

Strength of connection elements:

Nozzle wall shear=PI/2*davg.*tn*Sa	=	578470 LB
Fillet weld shear=PI/2*dout.*leg*Sa	=	405771 LB

Strength paths:

1−1= Nozzle wall shear + Fillet weld shear	=	984241 LB
2−2= Inner+ Outer Fillet weld shear	=	811542 LB

MANWAYS

PARAGRAPH UG−37 REINFORCEMENT REQUIRED FOR OPENINGS IN SHELLS AND FORMED HEADS
For internal pressure tr and trn are the values required for the internal design pressure.

Reinforcing element to be made from shell plate.

Dp = 32.000 IN te = 0.625 IN

Required area

A =d*tr*F+2*tn*tr*F*(1−fr1) = 1.46 IN^2

Area available in shell; use larger value −

A1=d*(E1*t−F*tr)−2*tn*(E1*t−F*tr)*(1−fr1) = 8.66 IN^2

or

A1=2*(t+tn)*(E1*t−F*tr)−2*tn*(E1*t−F*tr)*(1−fr1) = 0.628 IN^2

Area available in nozzle projecting outward; use smaller value −

A2=5*(tn−trn)*fr2*t = 0.895 IN^2

or

A2=2*(tn−trn)*fr2*(tn+te) = 0.722 IN^2

Area available in nozzle projecting inward −

A3=2*(tn−c)*fr2*h = 0.469 IN^2

Area available in nozzle projecting outward weld −

A41=(leg)^2*fr2 = 0.128 IN^2

Area available in outer weld −

A42=(leg)^2*fr2 = 0.072 IN^2

Area available in nozzle projecting inward weld −

A43=(leg)^2*fr2 = 0.128 IN^2

Area available in element −

A5=(Dp−d−2*tn)te*fr4 = 5.000 IN^2

Total area available for reinforcement −

A1+A2+A3+A41+A43+A5 = 15.17 IN^2

For external pressure tr and trn are the values required for the external design pressure.

Required area

A =(d*tr*F+2*tn*tr*F*(1−fr1))/2 = 5.95 IN^2

Area available in shell; use larger value −

A1=d*(E1*t−F*tr)−2*tn*(E1*t−F*tr)*(1−fr1) = 0.000 IN^2

or

A1=2*(t+tn)*(E1*t−F*tr)−2*tn*(E1*t−F*tr)*(1−fr1) = 0.000 IN^2

Area available in nozzle projecting outward; use smaller value –

A2=5*(tn–trn)*fr2*t	=	0.904 IN^2
or		
A2=2*(tn–trn)*fr2*(tn+te)	=	0.730 IN^2

Area available in nozzle projecting inward –

A3=2*(tn–c)*fr2*h	=	0.469 IN^2

Area available in nozzle projecting outward weld –

A41=(leg)^2*fr2	=	0.128 IN^2

Area available in outer weld –

A42=(leg)^2*fr2	=	0.072 IN^2

Area available in nozzle projecting inward weld –

A43=(leg)^2*fr2	=	0.141 IN^2

Area available in element –

A5=(Dp–d–2*tn)*te*fr4	=	5.000 IN^2

Total area available for reinforcement –

A1+A2+A3+A41+A43+A5	=	6.54 IN^2

PARAGRAPH UW–16 MINIMUM REQUIREMENTS FOR ATTACHMENT WELDS AT OPENINGS

(d) Neck Attached by Fillet or Partial Penetration Welds. Figure 16.1 (s).

Throat of weld tc shall not be less than the smaller of 1/4" or .7 tmin.
Throat of weld tw shall not be less than .7 tmin.
Throat of reinforcing element outer weld shall not be less than .5 tmin.

tmin=lesser of 3/4", t or tn	=	0.375 IN
tc	=	0.250 IN
tw	=	0.263 IN
Throat of reinforcing element outer weld	=	0.188 IN
Minimum leg of weld tc	=	0.357 IN
Minimum leg of weld tw	=	0.375 IN
Leg of reinforcing element outer weld	=	0.268 IN

PARAGRAPH UG–41 STRENGTH OF REINFORCEMENT

(b)

(1) W 1–1=(A2+A41)*S	=	14863 LB
W 2–2=(A2+A3+A41+A43+2*tn*t*fr1)*S	=	25298 LB
W 3–3=(A2+A3+A5+A41+A42+A43+2*tn*t*fr1)*S	=	114054 LB
(2) W =(A–(d–2*tn)*(E1*t–F*tr))*S	=	25500 LB

PARAGRAPH UG–45 NOZZLE NECK THICKNESS

(c) Allowable stress in shear for nozzle neck	=	12250 PSI

PARAGRAPH UW-15 WELDED CONNECTIONS

(c) Allowable stress in welds:

Shear in outward nozzle fillet	=	8575	PSI
Shear in inward nozzle fillet	=	8575	PSI
Shear in outer element fillet	=	8575	PSI
Tension in element groove weld	=	12950	PSI

Strength of connection elements:

Nozzle wall shear=PI/2*davg.*tn*Sa	=	170474	LB
Inward fillet weld shear=PI/2*dout.*leg*Sa	=	121226	LB
Outward fillet weld shear=PI/2*dout.*leg*Sa	=	115454	LB
Element fillet weld shear=PI/2*Dp*leg*Sa	=	174358	LB
Element grve. weld tension=PI/2*dout.*te*Sa	=	305127	LB

Strength paths:

1-1= Nozzle wall shear + Element fillet weld shear	=	344833	LB
2-2= Inward + Outward fillet weld shear + Element groove weld tension	=	541807	LB
3-3= Inward fillet weld shear + Element fillet weld shear	=	295585	LB

SUPPORT SKIRT

Per Appendix G paragraph 5 (b) the mean diameter of the skirt is to coincide with the mean diameter of the shell to to minimize local stresses. The height of the skirt (height of the bottom tangent line) is to be two inlet nozzle diameters plus the depth of a head.

Dmskirt =	516.496	IN	Height =	369	IN
Dmskirt =	43.0	FT	Height =	30.8	FT

PARAGRAPH UG-23 MAXIMUM ALLOWABLE STRESS VALUES

(b) Maximum allowable longitudinal compressive stress shall be the lesser of the allowable tensile stress or the value of B.

(d) For the combination of earthquake loading or wind loading with other loads the allowable stress found in (b) can be increased by 20%.

Tangent modulus - E = 2.77E+07 PSI

COMPRESSIVE LOADS -	Weight of sorbent	=	304962	LB
	+ Weight of internal structure	=	38595	LB
	+ Weight of vessel	=	212684	LB
	Total weight	=	556241	LB

Required thickness for compressive load -	t=	0.220	IN
Required outside radius of shell -	Ro=	258.473	IN
Stress due to compressive load -	S=	1558	PSI

A = 0.125/(Ro/t) = 1.06E-04 B=1.2*A*E/2= 1768 PSI

Bending moment due to wind load –	M=	356461 FT–LB
Required thickness for wind load –		
t = M/(PI*R^2*Sa*E) =		0.012 IN
Bending moment due to earthquake load –	M=	1041537 FT–LB
Required thickness for earthquake load –		
t = M/(PI*R^2*Sa*E) =		0.034 IN
Total required thickness for combined loads –	t=	0.254 IN
Actual thickness of skirt –	t=	0.375 IN
Actual thickness of skirt plus corrosion allowance –	t=	0.500 IN

PARAGRAPH UG–37 REINFORCEMENT REQUIRED FOR OPENINGS IN SHELLS AND FORMED HEADS

Opening required for the flue gas inlet duct, duct diameter + 12 inches = 132.00 IN

Reinforcing element to be made from skirt plate. Use element inside and outside.

Dp = 156.000 IN te = 0.375 IN

Required area		
A =(d*tr*F+2*tn*tr*F*(1–fr1))/2	=	16.75 IN^2
Area available in shell; use larger value –		
A1=d*(E1*t–F*tr)–2*tn*(E1*t–F*tr)*(1–fr1)	=	15.998 IN^2
or		
A1=2*(t+tn)*(E1*t–F*tr)–2*tn*(E1*t–F*tr)*(1–fr1)	=	0.182 IN^2
Area available in nozzle projecting outward; use smaller value –		
A2=2*(tn–c)*fr2*h	=	0.469 IN^2
Area available in nozzle projecting inward –		
A3=2*(tn–c)*fr2*h	=	0.469 IN^2
Area available in nozzle projecting outward weld –		
A41=(leg)^2*fr2	=	0.128 IN^2
Area available in outer weld –		
A42=2*(leg)^2*fr2	=	0.143 IN^2
Area available in nozzle projecting inward weld –		
A43=(leg)^2*fr2	=	0.141 IN^2
Area available in element –		
A5=2*(Dp–d)*te*fr4	=	18.000 IN^2
Total area available for reinforcement –		
A1+A2+A3+A41+A43+A5	=	35.35 IN^2
Weight of skirt –	=	88385 LB
Total bearing load –	=	644626 LB

Base plate centerline shall match mean diameter of skirt. Gusseted chair type anchor bolting to be used.

Base plate:

Width	=	8.000 IN	Thickness	=	1.000 IN
Bearing load	=	99 PSI			
Bolt circle	=	523.996 IN	Bolt diameter	=	1.000 IN
Number of bolts	=	27	Chord length	=	60.832 IN

DISTRIBUTOR GRID SUPPORT STRUCTURE

MATERIALS OF CONSTRUCTION

	DESIGNATION	ALLOWABLE STRESS
BEAMS	SA–36	14500 PSI
SUPPORT CHAIRS	SA–36	12700 PSI

MODULUS – E = 2.77E+07 PSI

NO. OF MAIN BEAMS = 4 SPACING C TO C = 8.600 FT

BEAM LOADING – w = 903 LB/FT

FIRST BEAM OFF VESSEL CENTER LINE –

LENGTH – L = 42.131 FT				
MAXIMUM BENDING MOMENT – Mmax = w*L^2/8		=	200358	FT–LB
MINIMUM SECTION MODULUS – Zmin = Mmax/Sa		=	165.8	IN^3
MAXIMUM SHEAR LOAD – Vmax = w*L/2		=	19022	LB
BEAM 27 WF 94 – 27" X 10"				
WEB AREA – Aw = 12.454 IN^2	WEIGHT	=	94	LB/FT
MMNT. OF INERTIA– I = 3266.7 IN^4	SECTION MODULUS – Z	=	242.8	IN^3
BENDING STRESS – Sb = Mmax/Z		=	9902	PSI
MAXIMUM SHEAR STRESS – Ss = Vmax/Aw		=	1527	PSI
MAXIMUM DEFLECTION – ymax = 5*w*L^4/(384*E*I)		=	0.707	IN
WEIGHT OF BEAM		=	3960	LB/BEAM

SECOND BEAM OFF VESSEL CENTER LINE –

LENGTH – L = 34.400 FT				
MAXIMUM BENDING MOMENT – Mmax = w*L^2/8		=	133572	FT–LB
MINIMUM SECTION MODULUS – Zmin = Mmax/Sa		=	110.5	IN^3
MAXIMUM SHEAR LOAD – Vmax = w*L/2		=	15532	LB
BEAM 24 WF 76 – 24" X 9"				
WEB AREA – Aw = 9.92 IN^2	WEIGHT	=	76	LB/FT
MMNT. OF INERTIA– I = 2096.4 IN^4	SECTION MODULUS – Z	=	175.4	IN^3
BENDING STRESS – Sb = Mmax/Z		=	9138	PSI
MAXIMUM SHEAR STRESS – Ss = Vmax/Aw		=	1566	PSI
MAXIMUM DEFLECTION – ymax = 5*w*L^4/(384*E*I)		=	0.490	IN
WEIGHT OF BEAM		=	2614	LB/BEAM

TOTAL WEIGHT OF BEAMS = 26299 LB

DISTRIBUTOR GRID PLATES

MATERIALS OF CONSTRUCTION

		DESIGNATION	ALLOWABLE STRESS
GRID PLATES		SA-240 TYPE 316	18100 PSI
MODULUS –	E =	2.59E+07 PSI	

DIMENSIONAL DATA

PLATE WIDTH	20 IN	WEB HEIGHT	6 IN
LOWER FLANGE WIDTH	2 IN	THICKNESS	0.105 IN

MOMENT OF INERTIA BY THE PARALLEL AXIS THEOREM –

TOP OF PLATE –	A1 =	2.100 IN^2	I1 =	0.0019294 IN^4
WEB –	A2 =	1.260 IN^2	I2 =	3.78 IN^4
LOWER FLANGE –	A3 =	0.420 IN^2	I3 =	0.0003859 IN^4
SECTION –	A =	3.780 IN^2		

NEUTRAL AXIS; FROM TOP OF PLATE – C1 = 1.748 IN
FROM BOTTOM OF PLATE – C2 = 4.462 IN

MOMENT OF INERTIA OF THE SECTION –
I = (I1+A1*d1^2)+ . . . +(In+An*dn^2)

I1+A1*d1^2 =	6.041 IN^4
I2+A2*d2^2 =	6.099 IN^4
I3+A3*d3^2 =	8.166 IN^4
I =	20.306 IN^4

GRID LOADING – w = 175 LB/FT

MAXIMUM BENDING MOMENT – Mmax = w*L^2/8	=	1618 FT–LB
MAXIMUM SHEAR LOAD – Vmax = w*L/2	=	188 LB
BENDING STRESS, TOP OF SECTION – Sb = Mmax*C1/I	=	1672 PSI
BENDING STRESS, BOTTOM OF SECTION – Sb = Mmax*C2/I	=	4266 PSI
MAXIMUM SHEAR STRESS – Ss = Vmax/Aw	=	149 PSI
MAXIMUM DEFLECTION – ymax = 5*w*L^4/(384*E*I)	=	0.041 IN
DISTRIBUTOR GRID PLATE WEIGHT	=	12296 LB
TOTAL WEIGHT OF INTERNAL STUCTURE	=	38595 LB